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The CHESHIRE Migration Experiment
A Summary Report

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EXECUTIVE SUMMARY

In 1976 the CHESHIRE nuclear weapons test was detonated in the fractured volcanic rocks of Pahute Mesa at the Nevada Test Site (NTS). Tritium, fission products, and residual fuel radionuclides were deposited in and around the explosion, which occurred at a depth of 542 m (1779 feet) below the water table. The U.S. Department of Energy, Nevada Operations Office, began an investigation of radionuclide migration at this site soon after the test. CHESHIRE is the only underground nuclear test conducted below the water table at the NTS that has been characterized before, immediately after, and for more than two decades following detonation. With the cessation of nuclear testing, CHESHIRE provides the only opportunity to evaluate the controls on the long-term evolution of the radionuclide transport associated with a single nuclear test. Understanding the long-term radiological consequences of the CHESHIRE nuclear test is important because a majority of the highest yield tests were detonated below the water table in transmissive volcanic rock aquifers beneath Pahute Mesa; data from this one test bound conceptual models of radionuclide transport for the entire testing area.

Comprehensive information on the CHESHIRE nuclear test including the nuclear yield of the test, size of the explosion cavity, test specific radionuclide inventories, and a compilation of the details of the radionuclide migration experiment including specific radionuclide concentrations in solid and fluid samples collected from 1976 through 1990 are included in a larger classified manuscript which will not be accessible to the general reader. This document represents a shorter, unclassified summary that presents the major ideas incorporated in the larger, classified data set.

At CHESHIRE the saturated zone consists of the Calico Hills rhyolite lava aquifer which is among the most transmissive volcanic rock aquifers at the NTS because of its widespread, laterally continuous fracture network. Regional down-gradient flow is complex but in the general south-southwest direction of the Oasis Valley discharge area.

The effects of the detonation included formation of an explosion cavity, melting and vaporization of the silicate host rock, incorporation of refractory radionuclides with high boiling points – including Pu – into the glass and subsequent creation of a collapse chimney which propagated upwards but did not reach the ground surface. Samples to support studies of radionuclide migration were taken soon after the test in 1976. The re-entry hole was renamed U-20n PS1 DD-H. Solid samples were taken from the slant re-entry hole before it was lined, the liner was subsequently perforated below the cavity region, and 19 m^3 of cavity fluids were pumped from the well. The well was recompleted higher in the cavity and extensively pumped again in 1983 and 1984 with production in excess of 1.3E4 m^3 of water. In 1985 the pump was withdrawn from the well and a bridge plug was inserted to isolate the cavity region. The casing was perforated outside the chimney to draw water from a transmissive shallow aquifer; at the conclusion of pumping, 3.5E4 m^3 of water had been produced from the well. In 1987 the UE-20n#1 satellite well was drilled approximately 300 m southwest of the CHESHIRE emplacement hole and completed in fractured lavas thought to intercept radionuclides moving down gradient from the CHESHIRE chimney. About 270 m^3 of water were pumped from the satellite well.

Studies of solid and fluid samples from CHESHIRE indicate the test cavity infilled quickly with water containing high concentrations of tritium (10^7 Bq/L) and other soluble radionuclides including ^{90}Sr, ^{106}Ru, and ^{125}Sb. ^{137}Cs and refractory radionuclides (e.g., ^{144}Ce) were found in low concentrations. Comparison of the predicted versus observed hydrologic source term for the CHESHIRE cavity indicate the effective volume in which the tritium was distributed was approximately twice that of the cavity; tritium was most likely well mixed throughout the collapse chimney which extends upward to the level of static water table.

Concentrations of ^{3}H, ^{85}Kr, ^{99}Tc, ^{106}Ru, ^{125}Sb, and ^{129}I in shallow samples collected above a bridge plug in 1985 are close to 1985 cavity concentrations. It is notable that these radionuclides are all non-sorbing, while concentrations of sorbing species – including ^{90}Sr and ^{137}Cs – were less than those measured in the cavity. Pu was not detected in water within the cavity or at the shallower interval above the cavity. The fluid dynamics of water infilling the thermally hot cavity may cause radionuclides to ascend by convention before being laterally dispersed through transmissive aquifers at shallower depths. Samples taken from the down gradient satellite well contain concentrations of ^{3}H, ^{99}Tc, and ^{129}I comparable to those measured above the bridge plug in the re-entry well. Sorbing radionuclides are strongly depleted in the satellite. These findings are consistent with the conservative down-gradient movement of non-sorbing radionuclides through a laterally transmissive aquifer. Radiochemical analyses of filtered and unfiltered waters from the CHESHIRE cavity indicated that most of the Mn, Co, Ce, and Eu isotopes were associated with colloid sized (< 450 nm) particles. The concentration of colloids in formation fluids collected from outside the cavity was approximately 50% of the concentration within the cavity; radionuclide activities outside the cavity were approximately 2.5% of the activities inside the cavity. These data suggest that colloids are removed during transport and colloids incorporate only a small amount of the radioactivity in the cavity. However, these data demonstrated the ability of colloids to transport radionuclides with lower solubilities (e.g., rare earth elements and actinides) outside of the detonation cavity.

Despite the existence of a volcanic dike which intruded the formation at the depth of the explosion, faulting of the volcanic formation, and a collapse chimney that did not reach ground surface, the CHESHIRE test and the post-test radiochemical and hydrologic environment is typical for high-yield, below-water-table tests conducted on Pahute Mesa. A model of radionuclide transport at CHESHIRE incorporating ascent of soluble radionuclides and colloids by the convection of thermally hot water and subsequent lateral migration through transmissive shallow volcanic aquifers has been further confirmed through recent studies of plutonium transport associated with the BENHAM test on Pahute Mesa. It is significant that relatively insoluble radionuclides can be transported outside the cavity region as colloids. Continued study of fluids pumped from the CHESHIRE cavity and chimney affords the opportunity to monitor the long-term solution, suspension, and transport of radionuclides in fractured volcanic rock aquifers characteristic of the Pahute Mesa testing area.

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ABSTRACT

The CHESHIRE nuclear weapon test was detonated in 1976 in fractured volcanic rock at the Nevada Test Site (NTS). This test is representative of many other high-yield tests conducted below the water table in the Pahute Mesa area of the NTS. Since 1976 we have been studying the movement of test-related radionuclides within a few hundred meters of the explosion cavity. CHESHIRE is the only nuclear test characterized before, immediately after, and for decades following the detonation and provides data on both the prompt and long-term dispersal of radionuclides after an underground nuclear test. For this reason it is a unique field-scale transport experiment. Solid and fluid samples were collected from a drill back hole extending into and through the cavity in order to measure the initial distributions of radionuclides after the detonation. We subsequently pumped and sampled water from the cavity region and from a hydraulically transmissive zone about 400 m higher in the collapse chimney. A satellite well was also drilled 380 m down gradient from CHESHIRE and intercepted radionuclides (including tritium in high concentration) being transported through transmissive aquifers. Studies of radionuclide migration at CHESHIRE documented for the first time at the NTS the transport of relatively insoluble radionuclides (e.g., europium isotopes) with colloids moving in the groundwater. Water was pumped again from the cavity and chimney horizons in 1998 in order to observe the evolution of the hydrologic source term after several decades. Recent comprehensive studies of the geology and hydrology at the CHESHIRE site have improved predictions of radionuclide migration in the context of a regional groundwater flow model. This report provides unclassified data and describes a conceptual model for radionuclide migration associated with a nuclear test that is applicable to other tests on Pahute Mesa similar in yield, hydrogeologic setting, and age.

I. INTRODUCTION

In 1973 the Radionuclide Migration (RNM) program was initiated by the U.S. Department of Energy, Nevada Operations Office (DOE/NV) to evaluate the radiological and hydrological consequences of underground nuclear weapons testing at the NTS (Hoffman et al. 1977). Participants in the RNM program included the Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), the U.S. Geological Survey (USGS), the Desert Research Institute (DRI) and several additional technical support organizations. The RNM program has evolved into DOE/NV's current Hydrologic Resources Management Program (HRMP) which was established in 1983 to support defense programs (e.g., underground nuclear testing and science-based stockpile stewardship) and environmental management at the NTS through an integrated field and laboratory program in radiochemistry.

Field studies at the site of the CAMBRIC and CHESHIRE nuclear tests provide unique insight to the migration of radionuclides in the post-test environment. Investigations of radionuclide migration studies at the CAMBRIC test site in saturated unconsolidated alluvial deposits in Frenchman Flat have been extensively documented (Bryant 1992). Data bearing on radionuclide transport at the 1976 CHESHIRE nuclear test located in fracture-flow volcanic aquifers of Pahute Mesa have been compiled but not as widely reported. The purpose of this report is to summarize historical interpretations of radionuclide migration associated with the CHESHIRE test. The summary is based upon a comprehensive review of test-specific data that remain classified. It is organized in nonclassified format to make the conclusions available to a wider audience. The present report may serve as a guide for those interested and authorized to examine the larger classified data set.

The studies conducted at the CHESHIRE site up through 1988 have assumed greater relevance in 1999 because of recent observations of radionuclide migration at other study sites on Pahute Mesa at the NTS (Kersting et al. 1999). Data from CHESHIRE are valuable especially because CHESHIRE was extensively documented before and after testing and because this test is similar to others in age, hydrologic setting, and yield. The CHESHIRE location is also significant because its position in western Pahute Mesa is representative of the other largest, below-the-water-table tests that are closest to potential off-site points of public water use. The 1976 CHESHIRE underground nuclear weapons test (detonated in the U-20n emplacement hole) was selected as a field experiment to evaluate the effect of high-yield underground nuclear tests on the hydrologic environment in volcanic aquifer systems of Pahute Mesa. Data from CHESHIRE are exceptional because they document both the prompt (< 1-year) radiologic source term residual from an underground, below-the-water-table nuclear explosion as well as the resulting hydrologic source term, defined as those radionuclides dissolved in or available for transport by groundwater (Kersting 1996). The data we summarize below document the evolution of the CHESHIRE radiologic and hydrologic source terms over almost two decades. This data set is unique for it permits analysis of the transition between the immediate dispersal of radioactive materials and subsequent migration involving physicochemical interactions with the regional aquifer system. These data provide information about the controls on radionuclide migration associated with high-yield [>200 kiloton (kt)] below-the-water-table tests conducted in fracture-flow volcanic aquifers at the NTS.

To date, CHESHIRE is one of four (DOE/NV) sponsored studies of radionuclide migration in fractured volcanic rocks of Pahute Mesa. The other Pahute Mesa volcanic aquifer study sites are the 1975 TYBO (U-20y)/1968 BENHAM (U-20c) tests, the 1990 BULLION (U-20bd) test, and the 1968 Schooner (U-20u) test (refer to Figure 1) (Smith 1998). The 1965 CAMBRIC test fired beneath Frenchman Flat and the 1976 CHESHIRE test are the underground weapons tests which have been most thoroughly characterized by the DOE/NV RNM program. Data from radionuclide migration studies at CHESHIRE contribute significantly to knowledge of what radionuclides are soluble, ranges in observed concentrations, and factors that affect radionuclide mobility.

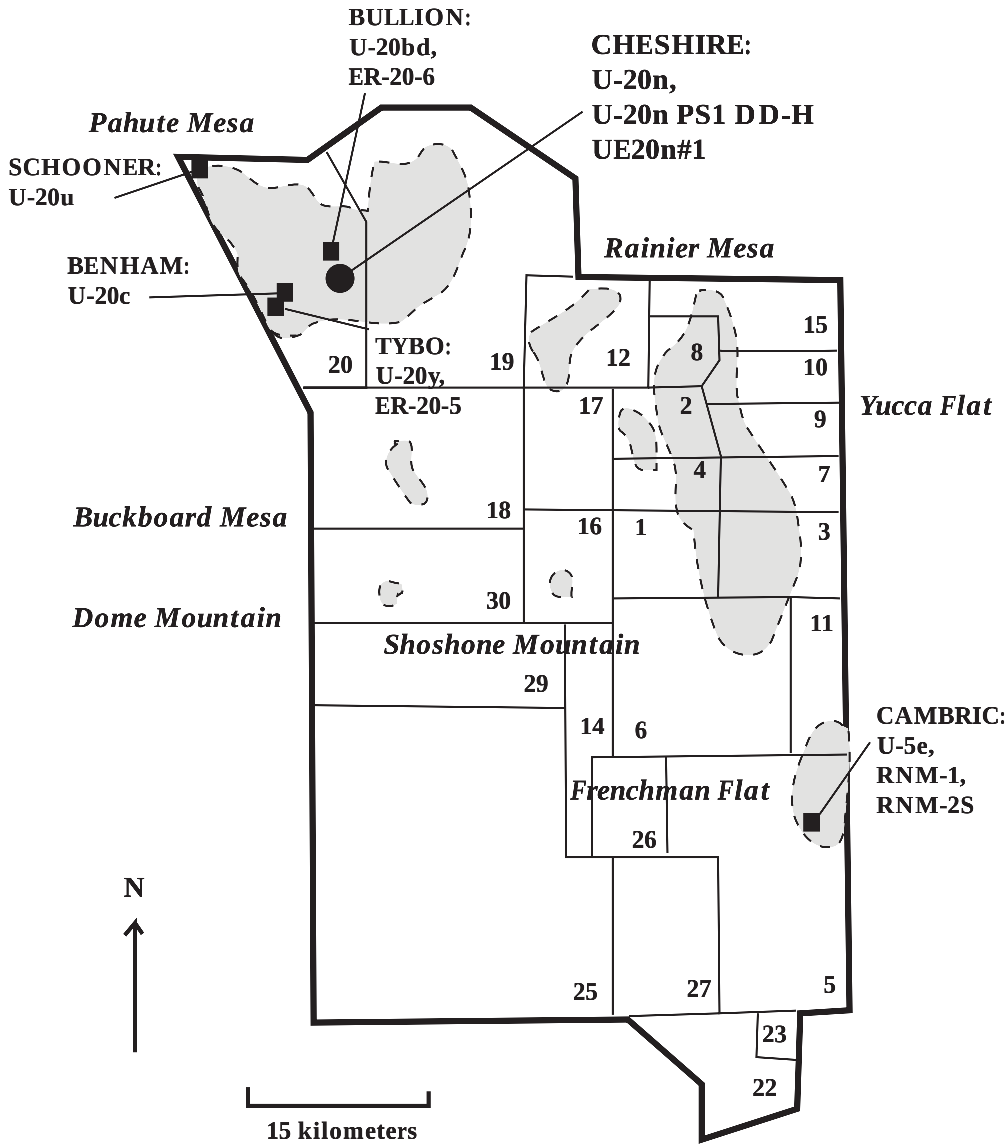

Figure 1. Principal underground nuclear testing areas (shaded) on the Nevada Test Site. Location of the CHESHIRE nuclear test (circle) includes holes U-20n, U20n PS1 DD-H, and UE20n#1. Other sites of radionuclide migration studies (squares) include TYBO (U-20y), BENHAM (U-20c) and the ER-20-5 well cluster, BULLION (U-20bd) and the ER-20-6 well cluster, SCHOONER (U-20u), and CAMBRIC (U-5e) and wells RNM-1 and RNM-2S.

CHESHIRE is a prototype field experiment to study contaminant transport. The site was selected to be a 'cradle-to-grave' study of the radiologic and hydrologic effects of underground nuclear testing. Considerable geologic and hydrologic information for the test environment was collected and a hydrologic test well (U-20a2) was drilled and tested for nearly a decade prior to the detonation of CHESHIRE. Water was sampled in the cavity region shortly after detonation in 1976 and additional water samples were obtained from1983 to 1987. These samples provide more radiochemical data and hydrologic information to define the hydrologic source term at CHESHIRE than at any other NTS underground test location. CHESHIRE provided (until 1995) the only evidence of high concentrations of tritium and other radionuclides outside the cavity region (> five cavity radii) (Thompson 1985-1989, Buddemeier and Hunt 1988; Buddemeier and others 1991; Erikson 1991) in volcanic aquifers of the Nevada Test Site. Studies at CHESHIRE also furnished initial evidence that radionuclides could move significant distances as colloids.

Data from this test and the interpretive models of test-specific explosion dynamics ('phenomenology') and radionuclide migration they support are important because CHESHIRE is similar to many other tests conducted prior to the 1976 Threshold Test Ban Treaty. CHESHIRE was a high-yield (200-500 kt) underground nuclear test detonated more than 300 m (1000 feet) below the water table in the Pahute Mesa testing area (Areas 19 and 20 of the NTS) on February 14, 1976. Expressed as a fraction of total underground radioactive yield, the majority of the 'groundwater-accessible' residual radionuclides at the Nevada Test Site were deposited within the Pahute Mesa testing area (Bryant and Fabryka-Martin 1991).

During the years of underground nuclear weapons testing from 1951 until 1992, 85 of the 828 underground nuclear explosions at the NTS were detonated in the Pahute Mesa testing area (Figure 1). The majority of the largest, high-yield (>200 kt) NTS tests were detonated at Pahute Mesa. These high-yield tests were detonated between 16 meters above and 822 meters below the pretest water table, and most were 500 to 800 meters below the water table (Laczniak et al. 1996). In addition, many intermediate yield (20-200 kt) Pahute Mesa tests were detonated at working points (WP) less than 50 m above the water table. These latter tests produced explosion cavities with high radionuclide concentrations at their lower margins that extended below the pre-test water table. Understanding the hydrogeologic setting of these large contaminant sources that are available to the regional groundwater system is critical to establishing effective strategies for groundwater protection and management at the Nevada Test Site.

The 1995 and 1996 drilling of Environmental Restoration (ER) program wells ER-20-5 at the U-20y TYBO test site and ER-20-6 at the U-20bd BULLION test site encountered high concentration plumes of tritium in ground water (Smith 1998; Kersting et al. 1999). Follow-up studies at these sites support the conclusions drawn from investigations at the CHESHIRE site. The combined results from all of these studies at CHESHIRE, TYBO/BENHAM, and BULLION permit more definitive statements to be made regarding radionuclide transport from high-yield, below-the-water table nuclear tests conducted in the fracture-flow volcanic aquifers of Pahute Mesa.

This report provides a synopsis of the results of historical investigations of radionuclide migration at the CHESHIRE test from 1976 to about 1987. Included are summaries of the geologic and hydrologic setting of Pahute Mesa and the U-20n CHESHIRE test site as well as a description of device emplacement, testing, phenomenology, and post-test operations. Radionuclide migration at the CHESHIRE site is discussed in the context of an abbreviated history of the RNM investigation, a summary of the radiologic as well as the expected and observed hydrologic source terms, and the relevance of the CHESHIRE experiment to studies of contaminant transport at the NTS. This report is a nonclassified companion to our comprehensive review of classified data and interpretative results from the CHESHIRE radionuclide migration experiment. The present report provides a short, unclassified summary of the major findings, results, and analyses that may be of interest to general readers.

II. GEOLOGIC AND HYDROLOGIC SETTING

A. Geology and Hydrogeology

1. Regional Geologic Setting

The geology of the CHESHIRE test site beneath Pahute Mesa is part of a volcanic aquifer system within rocks of the southwestern Nevada volcanic field (Figure 2). The subsurface of Pahute Mesa consists of silicic volcanic rocks deposited largely within the Silent Canyon caldera complex. The volcanic units in Pahute Mesa consist of rhyolite welded tuff, lava flows,

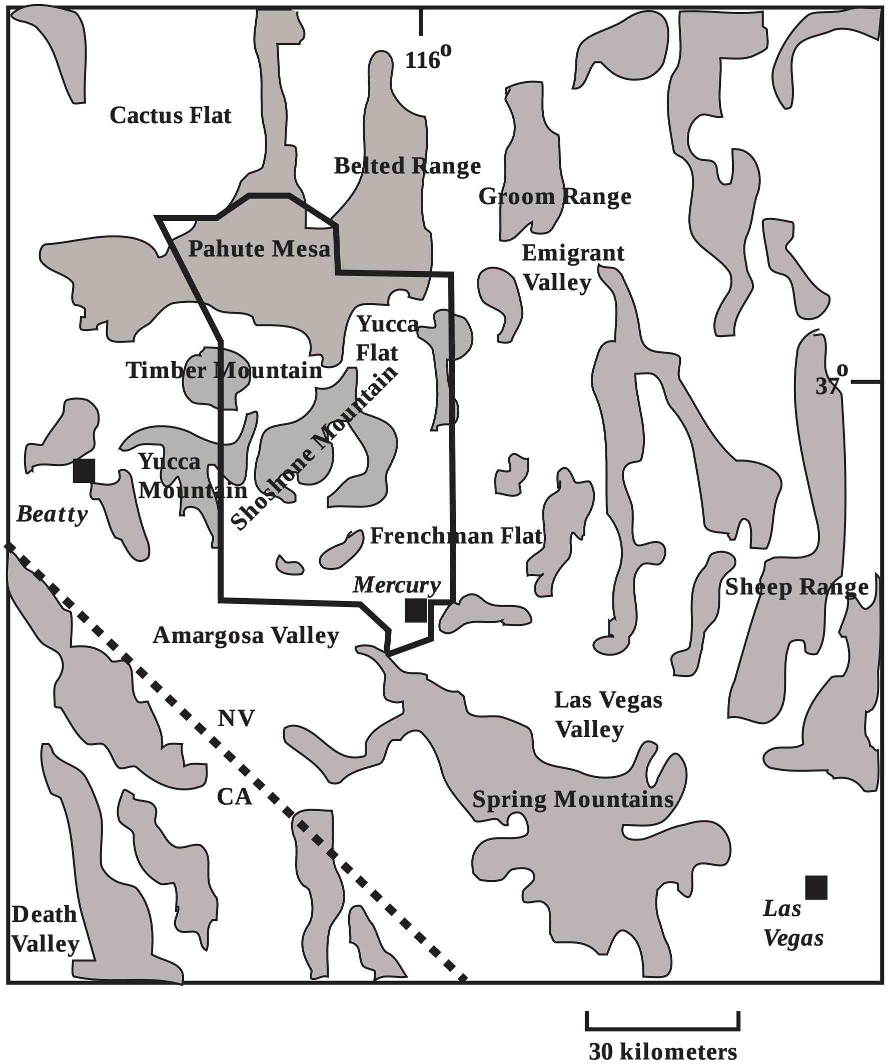

Figure 2. Location of the Nevada Test Site (outlined) and physiographic features in southern Nevada.

and related nonwelded ash-fall and pyroclastic tuff deposits of the middle and late Miocene (16-9 million years ago (Ma)) southwestern Nevada volcanic field. In the lava flows and welded tuff deposits, most groundwater flows within fracture-flow systems rather than by porous-media flow (Blankennagel and Weir 1973). Lava flows, domes, and related tuff deposits form a complex pattern of lenticular fractured aquifers separated by irregular masses of less transmissive nonwelded zeolitized deposits that interfinger and surround the lava flows and domes (Laczniak et al. 1996). Thick welded ash-flow tuff sheets form the principal aquifer units in southwestern Pahute Mesa, especially in the shallower part of the saturated zone. The entire stratigraphic and lithologic package is offset by younger high-angle normal faults. Recent summaries of the geology and hydrogeology of this volcanic field are contained in Laczniak et al. (1996); Sawyer et al. (1994); Ferguson et al. (1994); Noble et al. (1991); Byers et al. (1989); and Sawyer and Sargent (1989).

Two major buried calderas of the southwestern Nevada volcanic field, which together form the Silent Canyon caldera complex, are located in the subsurface of the Pahute Mesa underground test area (Figure 3). These two calderas are the Grouse Canyon caldera, located to the

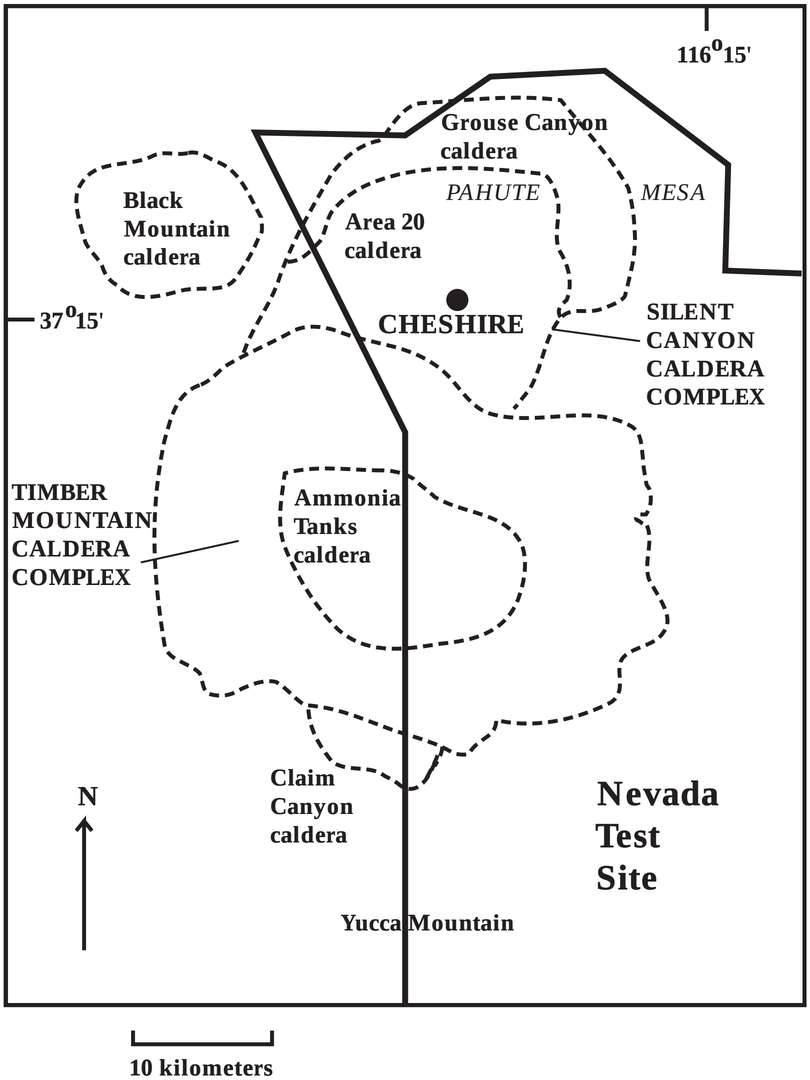

Figure 3. Caldera complexes in the northwestern Nevada Test Site. The Silent Canyon caldera complex underlies Pahute Mesa.

northeast, and the younger Area 20 caldera, to the southwest (Sawyer et al. 1994, and Sawyer and Sargent 1989). The Timber Mountain caldera complex to the south (Figure 3) later truncated the Silent Canyon caldera complex. The hydrostratigraphic units of the Area 20 caldera in central and southern Area 20 (Figure 1) are principally rhyolite lava flow aquifers of the Calico Hills Formation. West of the high-angle Boxcar fault (Figures 3, 5) these lava-flow aquifers are overlain by more transmissive welded tuff aquifers of the younger Paintbrush Group (the Topopah Spring Tuff and Tiva Canyon Tuff) erupted from calderas south of Pahute Mesa. The Calico Hills lava-flow aquifer in southwest Area 20 is thicker and more extensive than elsewhere beneath Pahute Mesa, and nonwelded tuff confining units are thin or absent. Hydrologic tests indicate that the Calico Hills rhyolite lava-flow aquifers and the overlying Paintbrush Group welded tuff aquifer act as an interconnected aquifer system (Blankennagel and Weir 1973).

The entire Silent Canyon caldera complex was buried about 11.5 Ma to a depth of 200 to 300 meters by Timber Mountain Group ash-flows erupted from the Timber Mountain caldera complex to the south. Subsequently, at approximately 9.5 Ma, Thirsty Canyon Group ash-flows from the Black Mountain caldera to the west (Sawyer et al. 1994) were deposited to form the uppermost layers of Pahute Mesa. The resulting extra-caldera ash-flow tuffs are tabular sheets that form the tableland topography of Pahute Mesa and the Thirsty Canyon drainage to the southwest, mantling the buried subsurface hydrogeology of the Silent Canyon caldera complex. These units are generally unsaturated, except west of the Silent Canyon caldera complex boundary. Total thickness of the combined volcanic section is typically greater than 3–4 kilometers.

2. Hydrogeology in the Vicinity of the CHESHIRE Test

The CHESHIRE test was detonated in western Pahute Mesa east of the Boxcar fault system within the Silent Canyon caldera complex. At the CHESHIRE site, the hydrogeology of the uppermost part of the saturated zone is dominated by the Calico Hills rhyolite lava aquifer (Blankennagel and Weir 1973). The Tiva Canyon and Topopah Spring Tuff are saturated west of the CHESHIRE site in Area 20. The combined thickness and relatively high hydraulic conductivity of these Paintbrush welded tuff units support the interpretation that the Paintbrush welded tuff aquifer is probably the principal hydrogeologic unit in the upper part of the saturated zone from the Boxcar fault to the limit of well control along the western NTS boundary. These welded tuff units are among the best volcanic aquifers in the Nevada Test Site region because of their widespread, laterally continuous fracture networks. Blankennagel and Weir (1973) report transmissivities of 50,000 gallons/foot/day for a pump test of the Paintbrush welded tuff aquifer in nearby borehole UE-20d. These transmissive welded tuff aquifers within Pahute Mesa have a relatively high potential for off-site radionuclide migration.

Eight years after the CHESHIRE detonation, R.G. Warren (Los Alamos National Laboratory, written communication, 1984), discovered that the working point geology at U-20n consisted of Calico Hills rhyolite lava intruded by a younger rhyolite dike. This observation provided evidence that the CHESHIRE test was the only working point in the Pahute Mesa, Rainier Mesa, or Yucca Flat testing areas that was located in a synvolcanic intrusive body. Subsequent detailed petrographic studies of samples from U-20n and the U-20a2 water well demonstrated that the working point lithology at U-20n CHESHIRE was identical to other rhyolite lava and dikes in a nearby borehole (U-20av). Both dikes correlated with a regional set of dikes known as the rhyolite of Windy Wash that occur northwest of Yucca Mountain in the moat of the Claim Canyon caldera. These dikes and related lavas are distinguished based upon their high contents of quartz, biotite, and hornblende. This interpretation quickly reconciled a number of anomalous features in the U-20n drill-site geology, e.g., the hydrologic ‘thief’ zone (discussed below), the interpretation of a fault in the vicinity of the CHESHIRE working point, and the occurrence of a crystal-rich rhyolite unit in the Area 20 lavas.

B. HYDROLOGY

1. Regional Hydrology

Groundwater in the area of the southwestern Nevada volcanic field and the NTS flows entirely within the Death Valley ground-water flow system (Winograd and Thordarson 1975, Waddell et al. 1984, Harrill et al. 1988; Laczniak et al. 1996; Thomas et al. 1996, Davisson et al 1999). Recharge areas for the Death Valley groundwater system are chiefly in the high mountain ranges of central and southern Nevada. Groundwater flows generally south to southwest through the NTS area to intermediate discharge areas at Oasis Valley and Ash Meadows (Winograd and Thordarson 1975), and to ultimate discharge areas in Death Valley in California (Figure 4). The Death Valley groundwater system is bounded to the east by regional confining unit rocks in the Desert Range, east of the NTS, and by the large recharge mound caused by the Sheep Range and Spring Mountains (Waddell et al. 1984). These features form a groundwater divide between the Death Valley groundwater system and Las Vegas, which is located in the eastern Nevada carbonate rock aquifer (Dettinger et al. 1995) that has its principal discharge area near Moapa in southeastern Nevada.

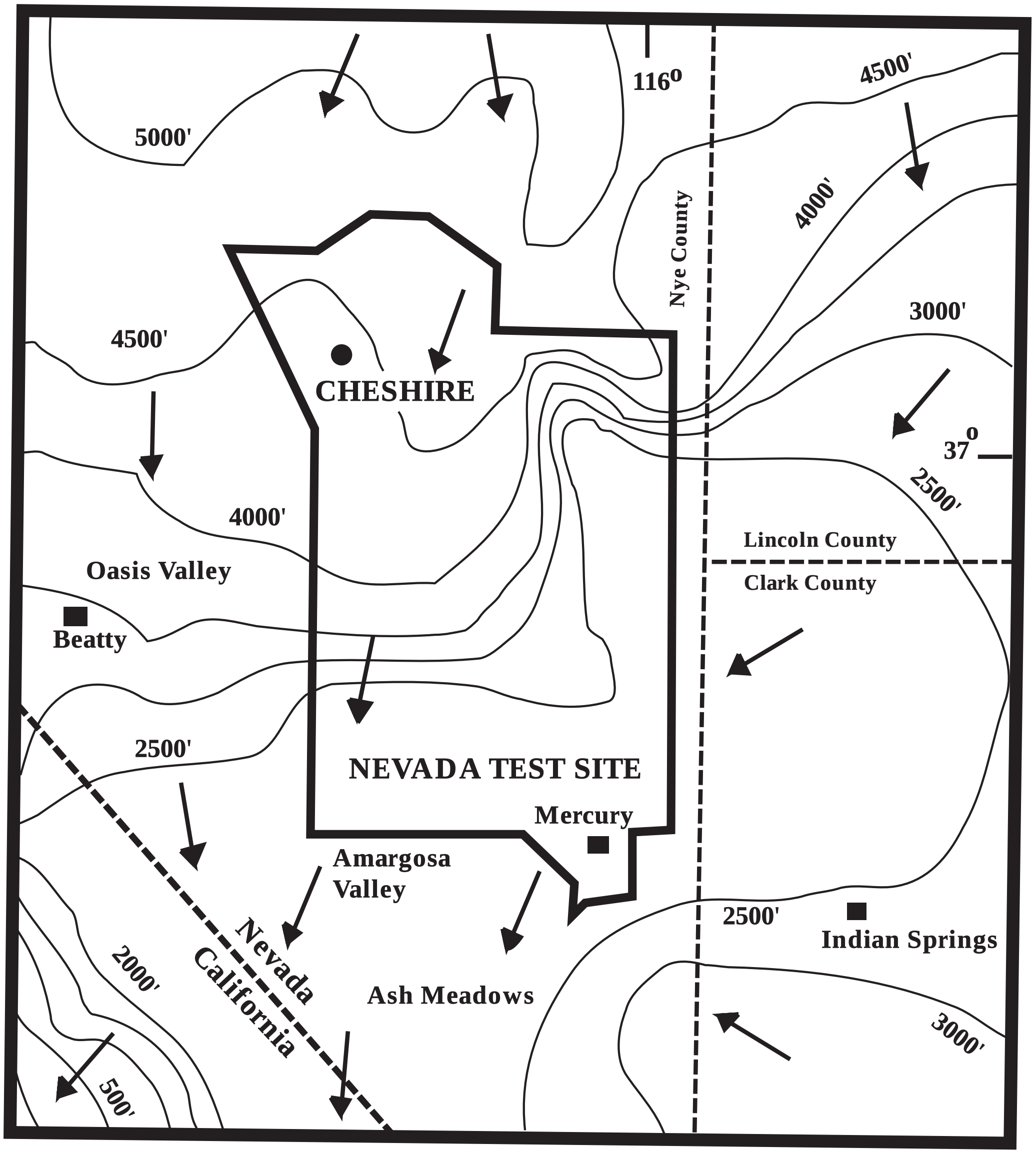

Figure 4. Generalized regional potentiometric surfaces (in feet above mean sea level). Inferred groundwater flow directions are shown by arrows (from Winograd and Thordarson 1975; Waddell et al. 1984; Laczniak et al. 1996.

Flow within the Death Valley groundwater system largely takes place within the regional carbonate aquifer rocks in the east and in volcanic aquifers in the west (Laczniak et al. 1996). Both systems eventually merge into carbonate aquifer rocks beneath the Amargosa Desert before flowing through the southern Funeral Mountains-Furnace Creek Wash-northern Black Mountain areas and discharging in Death Valley (Waddell et al. 1984, Laczniak et al. 1996). Groundwater subbasins within the Death Valley groundwater system have been proposed to account for the local variations in the water table elevations observed in the NTS area. The two major subbasins in the Death Valley groundwater system are the: 1) Ash Meadows subbasin to the east (Winograd and Thordarson, 1975; Laczniak and others 1996), dominated by groundwater flow in the carbonate aquifer; and 2) the Alkali Flat-Furnace Creek Ranch subbasin to the west (Waddell et al. 1984; Laczniak et al. 1996), dominated by volcanic aquifers in the region of the NTS. These two major subbasins are separated by a regional confining unit of Devonian-Mississippian impermeable sedimentary rocks that can be traced southwestward from between Yucca Flat and Pahute Mesa to northern Yucca Mountain (Figure 2).

In the western NTS area, groundwater flows within volcanic aquifers in the Alkali Flat-Furnace Creek Ranch subbasin (Waddell et al. 1984). The western boundary of this complex flow system is poorly defined and controversial. Contrasting interpretations suggest groundwater flows to the Oasis Valley discharge area from only the northwest corner of Pahute Mesa (Blankennagel and Weir 1973, Waddell et al. 1984) or flows from the entire NTS Pahute Mesa testing area (Borg et al. 1976, Laczniak et al. 1996). This distinction is critical because the groundwater beneath the Pahute Mesa testing area contains the greatest fraction of radionuclides introduced by underground nuclear testing (Bryant and Fabryka-Martin, 1991). It is also the shortest distance (~ 30 kilometers) from contaminant sources on the NTS to off-site points of discharge and public water use in Oasis Valley, north of Beatty, Nevada.

2. Hydrology of Pahute Mesa and the CHESHIRE Test Site

On a local scale in western Pahute Mesa, uncertainties in the pathways to the ultimate discharge point (Death Valley) for the hydrologic system are reflected in uncertain directions of groundwater flow between individual test sites and the NTS boundary. O'Hagan and Laczniak (1996) characterize the boundary between the northwestern NTS part of Pahute Mesa and the rest of the Pahute Mesa testing area on the Nevada Test Site as a water-level discontinuity. Earlier hydrogeologic work by Blankennagel and Weir (1973) had hypothesized that this zone was a south-southwest striking groundwater barrier, bounded on the east by a groundwater drain. The origin, extent, and significance of this disconformity remains uncertain pending further data from additional wells to be drilled in the area (Laczniak et al. 1996).

Water-level contours indicate that most of eastern Pahute Mesa is part of a southwesterly flowing regional aquifer system that conveys groundwater down gradient from the areas of recharge and regional groundwater inflow (Figure 5). In detail, however, flow is probably more complex because of downward vertical head gradients in eastern Pahute Mesa, and upward hydraulic gradients in the western Pahute Mesa setting of the CHESHIRE test site (Blankennagel and Weir, 1973). West of the water-level discontinuity described above, O'Hagan and Laczniak (1996) contoured water levels to indicate a southwesterly flowing groundwater system. Based upon these interpretations, central Pahute Mesa groundwater would flow southwest to the Timber Mountain caldera complex, and then toward Oasis Valley. An alternative hypothesis advanced by the Desert Research Institute (DRI) suggests that water levels define a south-trending trough based upon different interpretation of the same water level data (Figure 6) (Brikowski and Mahin 1993). A consequence of this southward flow model is the south flow of groundwater into the Timber Mountain caldera complex, and possibly beneath Yucca Mountain as proposed by Waddell and others (1984). New hydrologic well data are needed south and west of testing in southwest Pahute Mesa to confidently discriminate: 1) which direction groundwater flows from the test areas; 2) which aquifer units are most effective in conveying water; and 3) whether groundwater passes southward beneath Timber Mountain or is deflected southwestward by a higher potentiometric surface in the Timber Mountain area. DOE/NV environmental programs are pursuing a Fiscal Year 1999 and Fiscal Year 2000 drilling program southwest of Pahute Mesa in Oasis Valley to better resolve groundwater-flow paths in this area (IT Corporation 1998).

The hydrology of the Pahute Mesa testing area around CHESHIRE was well characterized during the exploratory drilling of Pahute Mesa during the mid-1960s (see Blankennagel and Weir 1973). U-20a-2, 91 m west of the U-20n emplacement hole, was one of 18 exploratory wells on which measurements were made of hydraulic characteristics including draw down pumping tests of transmissivity, packer tests of head on specific intervals, thermal logs of geothermal gradient, borehole geophysical logs,

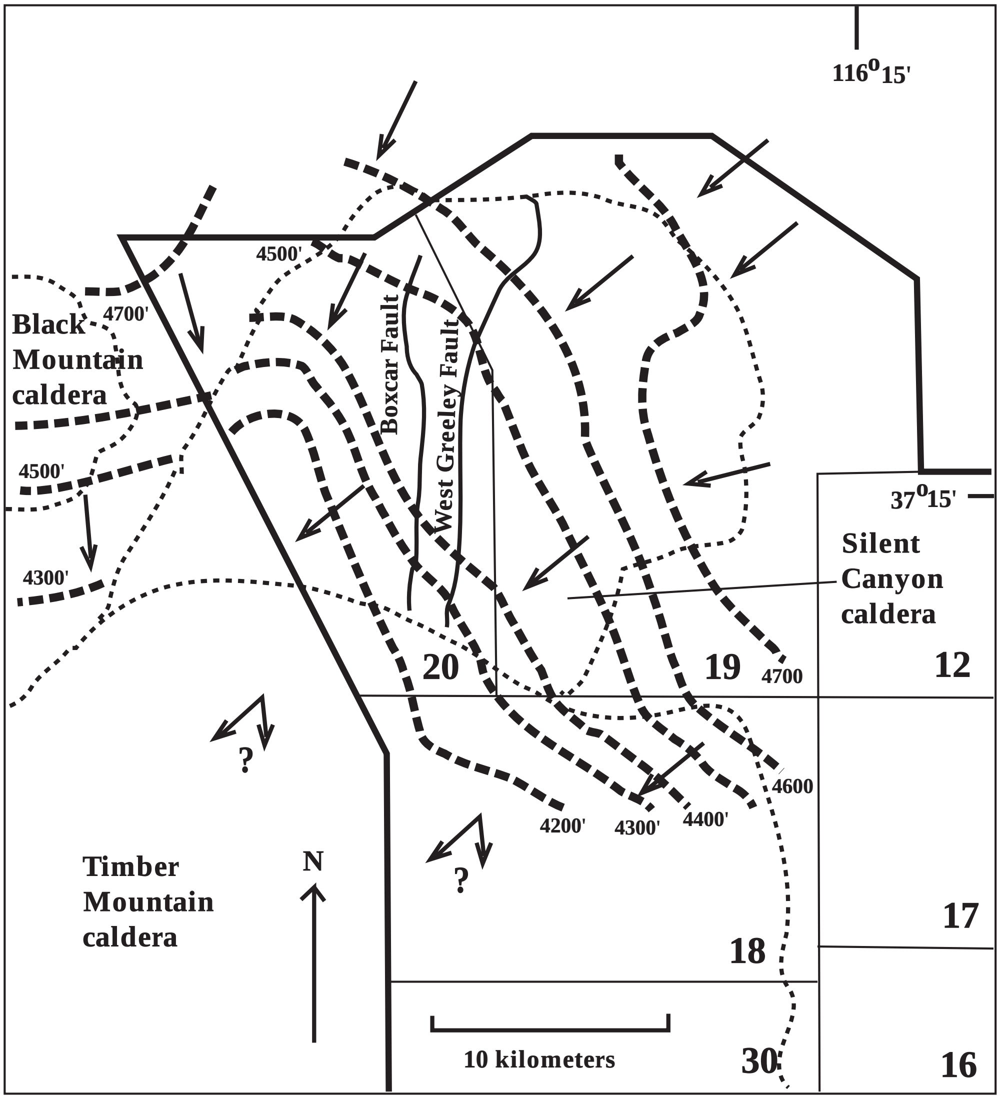

Figure 5. Major controls on ground-water flow in the Pahute Mesa area. After Laczniak et al. (1996) and O'Hagan and Laczniak (1996). Dashed water level contours in feet; datum in sea-level. Major caldera complex boundaries shown by dotted lines. Inferred direction of groundwater flow shown by arrows.

and analyses of water chemistry. Despite the abundance of relatively transmissive lava-flow aquifer rocks, the measured transmissivity of lava-flow aquifers in U-20a-2 was moderate: 18,000 gallons per day per foot, with a specific capacity of 8 gallons per minute per foot, and a yield of 186 gallons per minute (Blankennagel and Weir 1973, Table 3). The values for transmissivity and specific capacity derived from a pumping test at CHESHIRE (Blankennagel and Weir 1973, Figure 6) are intermediate between those of the most productive rhyolite lava-flow aquifers in northeast Pahute Mesa, and the very low yields of wells in north central Pahute Mesa (Blankennagel and Weir 1973, Figure 9).

Hydrologic heads in the Calico Hills rhyolite aquifer in exploratory hole U-20a-2 increase with depth as is typical in western Pahute Mesa where upward hydraulic gradients are commonly observed (Blankennagel and Weir 1973, Figure 10). The $NaHCO_3$ component in formation water at CHESHIRE is found commonly within the Silent Canyon caldera complex (see Blankennagel and Weir 1973, Figure 11, Table 10). Predetonation thermal measurements for U-20a-2 indicated a maximum bottom-hole

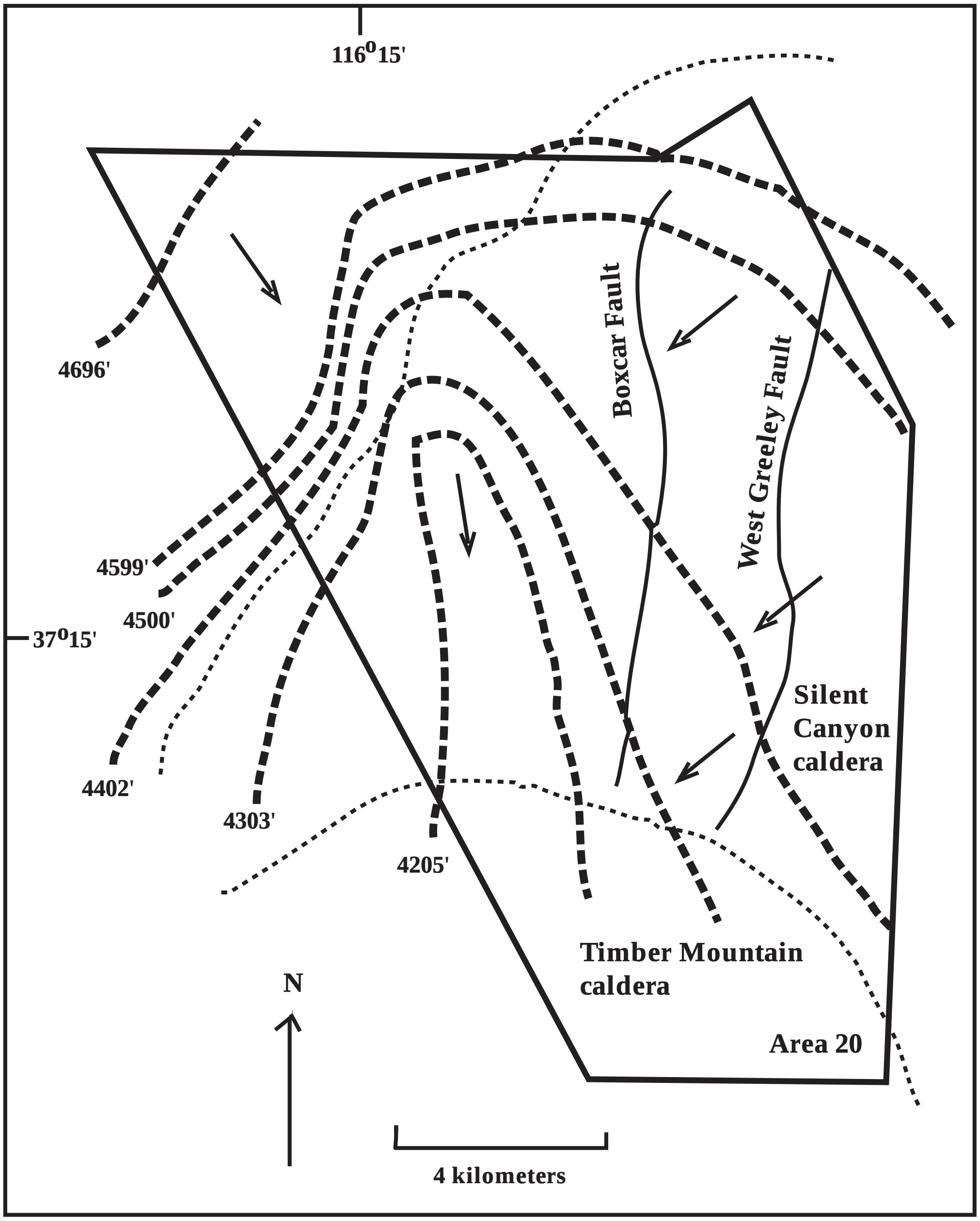

Figure 6. Alternate interpretation for groundwater flow in the Pahute Mesa area proposed by Desert Research Institute (after Brikowski and Mahin 1993). Dashed water line contours in feet; datum is sea-level. Inferred groundwater flow direction shown by arrows. Major caldera boundaries shown by dotted lines.

temperature of 41.1º C and a thermal gradient of 0.63º C per 100 feet (30 m) (see Blankennagel and Weir 1973, Table 8). The thermal gradient is low and perhaps corresponds to a higher lateral and vertical groundwater flux (i.e., the highest transmissivity wells have the lowest geothermal gradients).

A hydrologic ‘thief zone’ (Blankennagel and Weir 1968) was encountered in the CHESHIRE device emplacement hole at a depth below 1232 m (4042 feet). The term ‘thief zone’ is used to indicate a hydrologic capture zone that is capable of accepting a large amount of water.

This unusual hydrologic phenomenon led Blankennagel and Weir (1968) to conclude that the U-20n emplacement hole had encountered a 'dry fractured reservoir below a depth of 1232 m (4042 feet)...it must be an isolated lenticular body completely sealed from the surrounding saturated rock' or 'a permeable lens surrounded by poorly permeable strata' (Blankennagel and Weir 1969). They went on to state that 'A local anomaly of this type has not been encountered in the many [at least six] years of hydraulic testing at Pahute Mesa'. This relatively soft interval was cored from 1235 m to 1238 m (4050 to 4061 feet) and described as 'shattered, glassy, devitrified and altered rhyolite and considerable reddish-brown clay...this broken rock...'. As discussed above, the origin and significance of the thief zone remained enigmatic at the time (April 1968), but was later recognized to be related to a silicic dike.

III. THE CHESHIRE TEST

A. The Nuclear Test

The CHESHIRE underground nuclear test took place in hole U-20n in the central part of Pahute Mesa at a depth of 1167 m (3829 ft) below ground surface. The depth in U-20n from ground surface to the pretest standing water level is 625 m (2050 ft). The device and associated diagnostic materials were contained in a watertight canister and water was pumped out to keep the hole dry during emplacement and stemming. Conventional techniques were employed to prevent gas leaks around the diagnostic cables and to provide adequate stemming and containment. The device was fired February 14, 1976; the announced yield range was 200-500 kt. There were no releases of radioactivity to the atmosphere within 24 hours nor were there any unusual post-test test effects. The rubble chimney did not collapse to the surface. Cavity collapse occurred probably within 27.5 hours post-test prior to initiation of post-test drilling operations on March 2 (Rambo 1997). Four sidetracks were drilled off the main drill back hole before debris samples satisfactory for device radiochemical analysis were obtained. The successful sidetrack, U-20n PSl DD, was completed and sampled by May 1, 1976 (Figure 7 and Figure 8).

B. Radiochemical Analysis of Post-test Debris

Radiochemical diagnostics for underground nuclear tests are performed on vitreous melt debris that are found in the bottom of the cavity created by the detonation. At the time of the explosion, the device vaporizes under the extreme temperatures (several times 10^7 degrees) and pressures (over 10^6 atmospheres) generated by the thermonuclear reaction. The resultant shock wave creates a plasma-filled cavity at ground zero; the cavity plasma consists of fission products, activation products, actinides, tritium, vaporized rock, and both condensable and incondensable gases (e.g., H_2O, CO_2, HT) from the vaporization of rock pore water. Approximately 70 tons of rocks are vaporized for every kiloton of yield. A compressional shock wave propagates radially away from the working point driving the cavity to expand spherically by momentum for 80 to 500 msec. During this time the expanding cavity loses energy by adiabatic transfer to the wall rock which results in shock melting adjacent to the edge of the cavity. The cavity reaches its maximum radius when the internal cavity pressure is equal to the lithostatic pressure generated by the elastic rebound of the media surrounding the working point. Melt is produced from the condensate of the device and rock vaporized by the explosion, shock melting, and host rock that is fused by the extreme thermal gradients along the periphery of the standing cavity. Within approximately 500 msec the standing cavity has reached its maximum dimension and the melt originating on the walls and roof coalesces on the cavity floor forming a puddle. Approximately 700 metric tons of rocks are melted for every kiloton of yield (Olsen 1967).

The gas begins to cool after losing energy to the surrounding rock. During the initial condensation radionuclides with higher boiling points (transition elements, rare earths, actinides, platinum group elements, and alkaline earths) become incorporated in the molten glass.

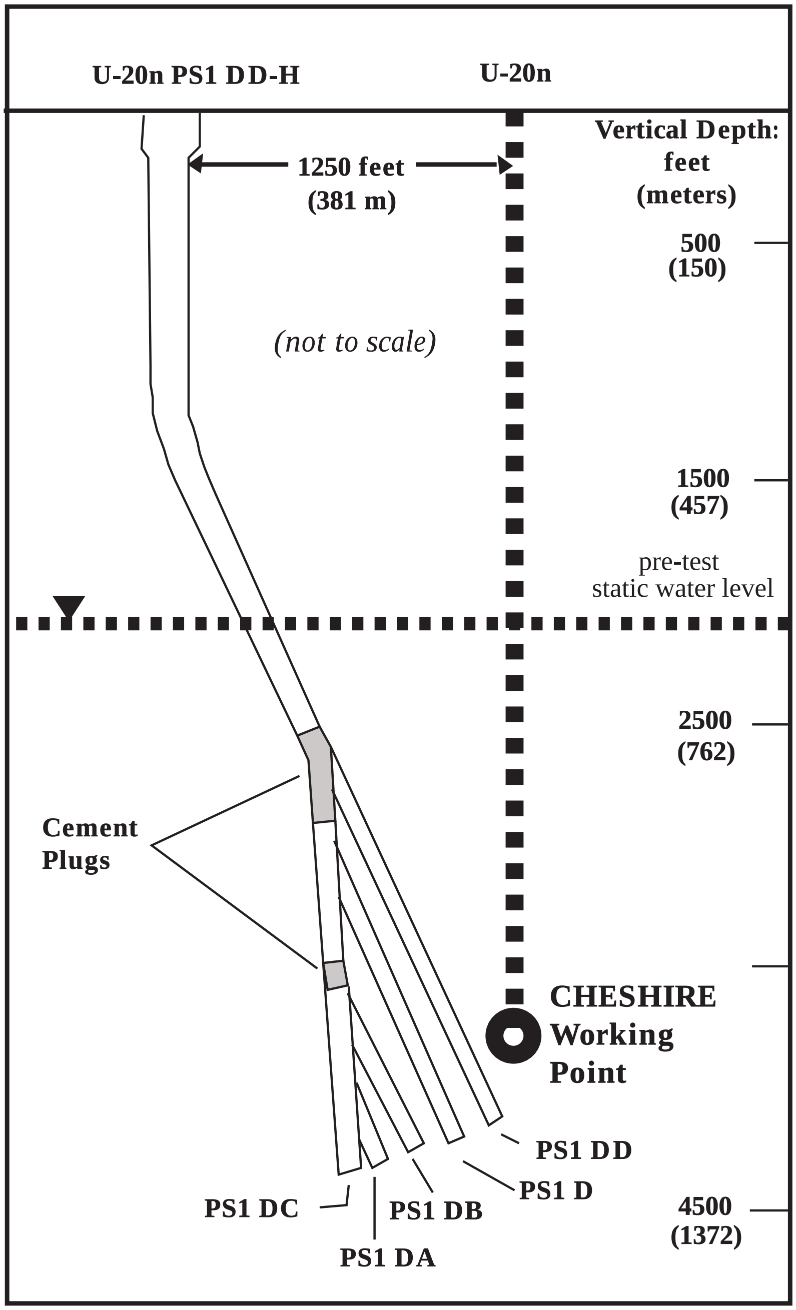

Figure 7. Vertical schematic of sidetrack holes associated with CHESHIRE drill-back. U-20n PS1 DD was the post-shot hole used for diagnostic debris sampling and hydrologic investigations. The hyrologic test hole is designated U-20n PS1 DD-H.

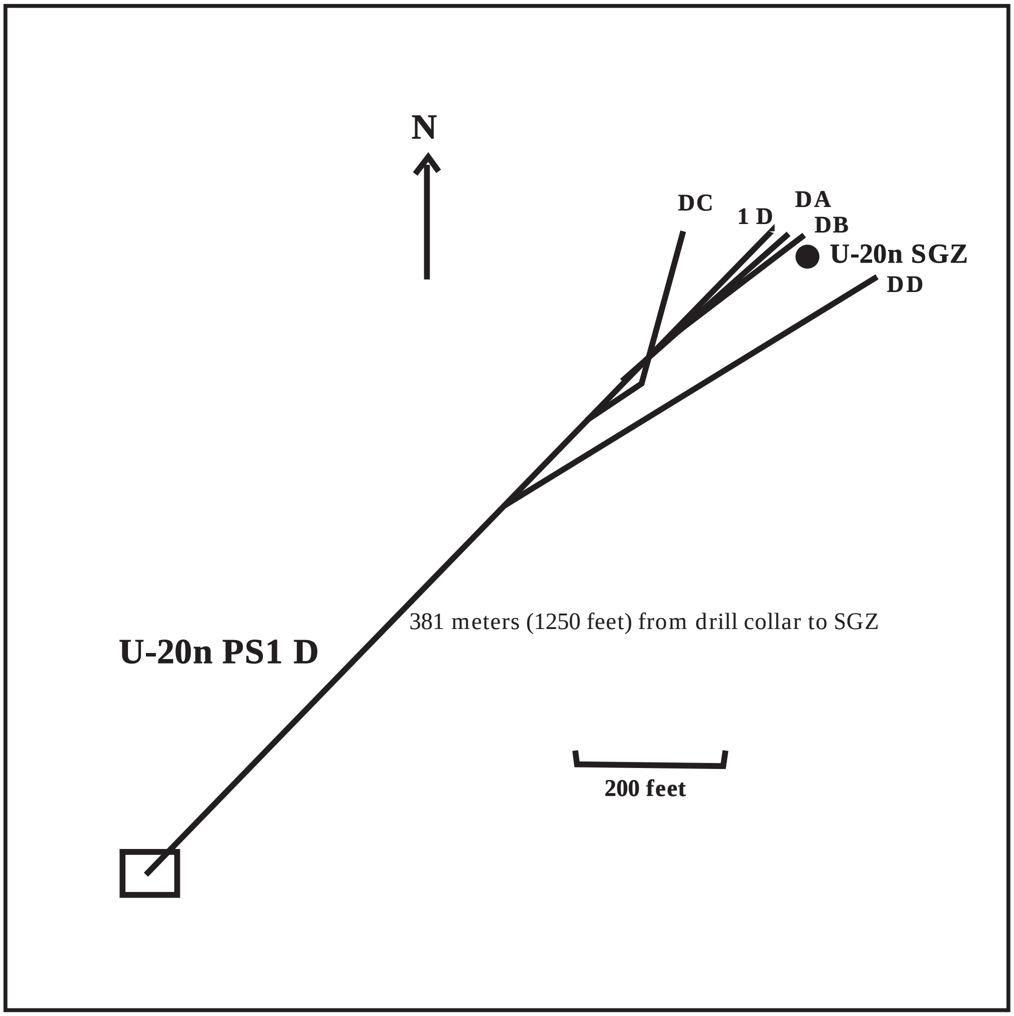

Figure 8. Plan view of U-20n surface ground zero (SGZ) and U-20n post-shot drillholes: U-20n PS1 D, PS1 DA, PS1 DB, PS1 DC, and PS1 DD.

For a discussion of fission product volatility, readers are referred to Bedford and Jackson (1965). Levy (1970) reports that ratios of refractory radionuclide species remain constant in the puddle glass while varying considerably in rubble samples associated with the subsequent collapse of the cavity. Based on radiochemical diagnostics collected from a variety of test materials, 95 ± 5% of the refractory species are contained in the melt fraction (Levy 1970). In a study of the 1966 PILE DRIVER test fired in Area 15 of the NTS, Borg (1975) notes that only 2 to 3% of the refractory elements are lost from ‘good’ puddle samples based on the consistency in gram concentrations of puddle material.

Heterogeneous partitioning of refractory radionuclides within the puddle glass was well documented during the 1994 re-entry drilling of the 1981 BASEBALL test in Yucca Flat (Thompson 1996). The BASEBALL device was fired in the nonwelded zeolitic tuff below the water table on Yucca Flat. Sidewall core samples were obtained in a nearly continuous vertical profile down the collapse chimney and through the cavity. The study concluded that, despite water saturation for more than a decade, the general pattern of radionuclide distribution was preserved from the time of the explosion. Refractory radionuclides were concentrated within the melt glass while volatile elements were more broadly distributed. Refractory radionuclides were not mobilized. ^{152}Eu, ^{154}Eu, and ^{155}Eu were identified exclusively in the melted fraction at the level of the working point.

The composition of the melt glass resembles that of the geologic media surrounding the working point. Electron microprobe analysis of the glasses produced during a nuclear explosion and the natural volcanic glass of the NTS indicates little variation in composition of the melt glass relative to the natural glasses (Borg 1975, Schwartz et al. 1984, Smith 1995a). Iron and calcium may be enriched in the explosive glasses because of incorporation of carbonate alluvium and/or steel from the down-hole test assembly at the time of explosion. Enrichments in alkalis, alkaline earths, and alumina indicate the presence of feldspathic minerals. X-ray diffraction studies indicate the glass is not entirely isotropic but also variably incorporates a crystalline component consisting of fractured quartz-feldspathic phases as well as minute Fe oxides formed during the quenching, annealing, or subsequent alteration of the glass.

Radiochemical diagnostics depend on obtaining debris which is representative of device performance. The ability to determine the 'bomb fraction' and account for geometric and chemical fractionation is extremely important in this enterprise. For this reason, considerable effort and time was expended at CHESHIRE to obtain good drill-back samples. The radiochemists who analyzed the CHESHIRE post-test samples reported that results from six cores indicated there was reasonably good mixing of the debris (Nethaway and Fontanilla 1976). In this case, individual cores were collected from locations separated from one another as far as 51 meters. LLNL radiochemists (Goishi and Wild 1995) stated that volatility was as predicted at CHESHIRE with no indication of significant fractionation affecting the cavity region. Based on the radiochemical diagnostic data, fission and fusion yields were calculated for the CHESHIRE test in 1976. Post-test data were re-examined in 1993 and 1994 (Smith 1995b) in support of a classified radionuclide inventory of all underground nuclear tests fired at the Nevada Test Site (Goishi et al. 1994).

C. Continued Use of the Drill-back Hole

In June of 1976 the drill-back hole was converted to a study site for radionuclide migration and renamed U-20n PS1 DD-H. At completion of the drill back, this hole was cased with 34 cm (13-3/8 inch) outside diameter casing to a slant depth (SD) of 737 m (2418 ft); the casing was cemented over the bottom 175 m (574 ft). The uncased 24 cm (9-7/8 inch) hole extended to a depth of 1316 m (4318 ft) SD. By this time, water had flowed back into the cavity/chimney region to a depth of 654 m (2146 ft) below ground surface, slightly below the depth to the pretest water level of 625 m (2050 feet).

IV. CHESHIRE AND THE RADIONUCLIDE MIGRATION PROGRAM

A. 1976 Sampling

The first RNM field study took place at Frenchman Flat and was focused on the CAMBRIC test conducted in unsaturated alluvium (reviewed by Bryant 1992); a second study site on Pahute Mesa was to provide data in contrasting hydrologic and geologic conditions representative of volcanic aquifer systems.

The RNM program selected the CHESHIRE test to study the movement of radionuclides away from an underground test in fractured volcanic rocks of Pahute Mesa. The experimental plan was to deepen the post-test drill-back hole so it extend below the bottom of the cavity, to collect solid samples in the cavity and chimney regions, and to set a liner in the hole. Then, by use of packers and perforations in the liner, water samples could be withdrawn from selected horizons. Work on the hole began June 21, 1976 (t_o + 128 days). The hole was deepened to a total depth of 1378 m (4520 ft) SD or approximately 1300 m (4280 ft) vertical depth (VD). Seventeen sidewall samples were collected in the cavity region between 1250 to 1310 m (4100 to 4300 ft) SD and a liner was emplaced between 608 m (1995 ft) and 1370 m (4495 ft) SD. Water samples initially collected within the liner contained no radioactivity. After it was discovered that the top of the liner was not completely sealed in the 34-cm (13-3/8 inch) casing, the connection was recemented. The joint between the casing and the liner created a constriction that was to hamper future down-hole operations.

Between September 10 and 12, 1976, three sets of perforations were made in the liner (and the annular cement) over the depth range 1322 to 1358 m (4337 to 4455 ft) SD in order to open it for water sampling. The intent was to obtain water from below the bottom of the cavity. A Reda pump was inserted in the hole with a USGS transducer attached and the first water was pumped out on September 13, 1976 (t_o + 212 days) (Figure 9). Various hydrologic tests and water sample collections were done until September 24, 1976, when an attempt was made to pull the pump and transducer. The plan was to pack off, perforate, and sample successively higher zones in the hole. Unfortunately, the pump stuck just below the top of the liner. During the next eight days efforts were made to retrieve the pump, but the net result was that the pump and miscellaneous pieces of cable, clamps, and sections of tubing were left firmly wedged at the top of the liner around 610 m (2000 ft) SD. Work at U-20n PS1 DD-H was stopped October 3, 1976.

The volume of water pumped in 1976 before the pump became stuck was 19 m^3 (5000 gals). Tritium was measured at concentrations up to 7.37E7 Bq/L; other radionuclides detected are listed in Table I in decreasing order of abundance. *All activities are referenced to t_o = February 14, 1976.* Concerted efforts were made during 1976 and 1977 to measure ^{239}Pu and ^{241}Am in the water samples from U-20n PS1 DD-H using radiochemical separation techniques based on traced samples and alpha counting; detection levels were on the order of 1E-3 Bq/L. However, actinides were not identified in this sample suite. Although ^{239}Pu was later reported as being "detectable" in the 1976 water, analytical

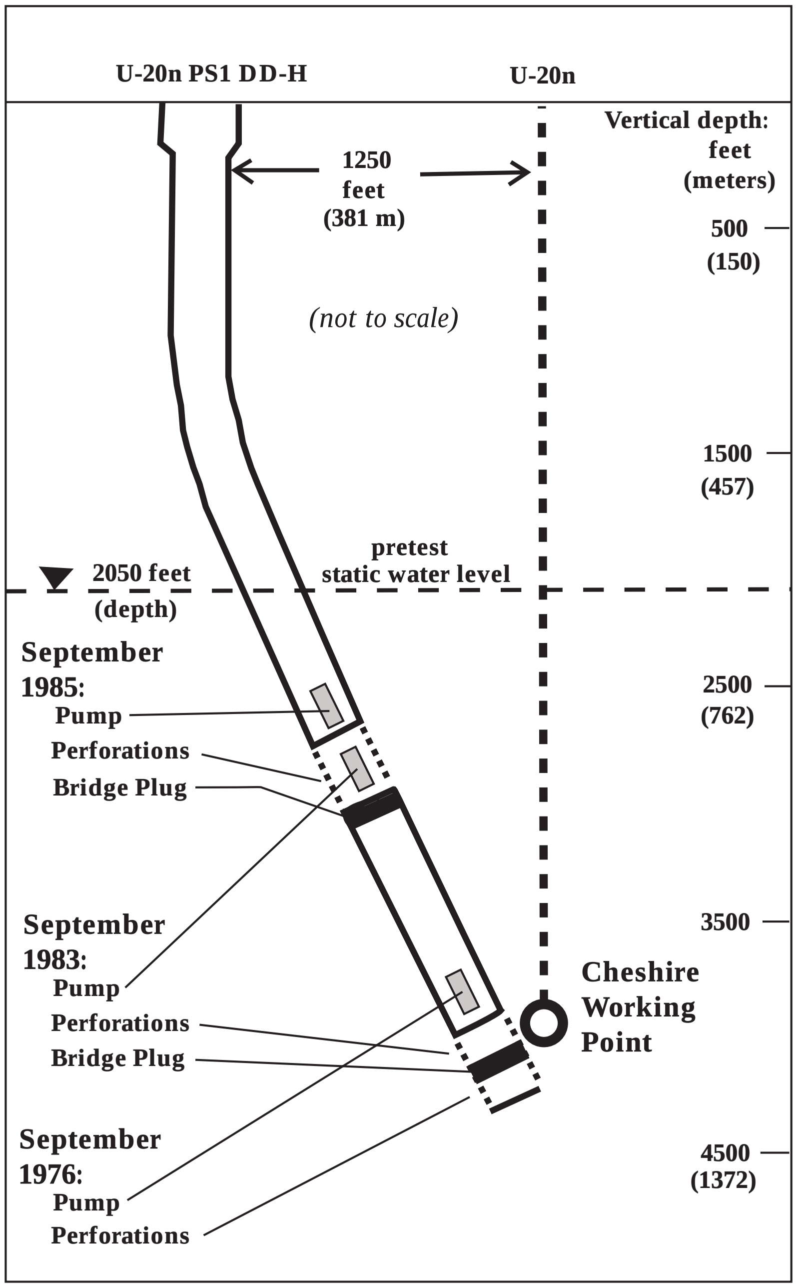

Figure 9. Schematic diagram of the configuration of the U-20n PS1 DD-H and depths of pumping between 1976 and 1985 (after Erikson 1991).

Table I. Radionuclides in 1976 Water Samples (activities corrected to t_o = February 14, 1976)

E7 Bq/L	E4 Bq/L	E3 Bq/L	E2 Bq/L	E1 Bq/L	Below Detection Levels
^{3}H	^{181}W	^{89}Sr	^{106}Ru	^{90}Sr	^{54}Mn, ^{59}Fe,
		^{103}Ru	^{124}Sb	^{125}Sb	^{58}Co, ^{60}Co,
		^{188}W			^{95}Zr, ^{123}Sn, ^{127}Te,
					^{137}Cs, ^{141}Ce, ^{144}Ce, ^{147}Pm, ^{160}Tb

results are inconclusive. If actinides were present in these samples, their concentrations were below levels at which quantitative measurements could be made. It is also notable that ^{137}Cs was at or below background levels in these water samples although it is often present in water close to nuclear test cavities.

Sidewall core samples were collected in the cavity region from depths below the working point at approximately 1233 m or 4046 ft SD prior to inserting the liner. These solid samples were collected at a higher elevation than the perforations through which the water samples were later pumped. Three cores were analyzed for tritium, ^{85}Kr, and gamma-emitting fission products. Water was extracted from the cores and analyzed for tritium and dissolved ^{85}Kr; the fission products were measured by gamma spectrometry. The tritium concentrations contained in the water from these cores were close to 1E7 Bq/L, somewhat lower than the maximum found in the pumped water. The ^{85}Kr concentrations were much less than those of tritium and decreased with depth in the hole. The core lowest in the hole registered measurable activity levels for only three radionuclides, all of which were volatile or had volatile precursors (^{89}Sr, ^{103}Ru, ^{137}Cs). The core sampled nearest to the working point contained higher concentrations of most radionuclides than the other cores. The data indicate that volatile and refractory materials were moderately fractionated over the 49-m interval between the two uppermost cores.

It is difficult to correlate the radionuclide contents of the water and core samples collected in 1976. Fluids from the vicinity of the cavity were likely mixed with water introduced into the hole on several occasions. Nevertheless, it appears that most of the more volatile radionuclides in the cores were also present in the cavity water.

B. 1983–1984 Sampling and Colloid Studies

After 1976, work at the CHESHIRE site was sporadic for several years. In 1981 the pump and other debris were dislodged and pushed to the bottom of the U-20n PS1 DD-H. A bridge plug was set at 1313 m (4309 ft) SD. In 1983 the hole was dewatered and the liner was perforated over the interval 1281 to 1306 m (4202 to 4285 ft) SD (Figure 9). In September 1983 about 519 m^3 (1.37E5 gals) of water were pumped from the perforated liner in U-20n PS1 DD-H at a rate of about 0.2 m^3/min (50 gpm). This water was analyzed for both dissolved radioactive and nonradioactive constituents. Analyses were performed on site and at institutional facilities by representatives of LANL, LLNL, and the USGS. Reynolds Electrical and Engineering Company (REECo) provided courier service and rapid analyses for tritium and lithium. Some of the same analytes were measured by several different organizations. Comparison of the results is complicated because of different sampling protocols and analytical methods. Also, radioactivity was reported in different units and referenced to different times. One reviewer of these data (Erikson 1991) has compiled the reported values from the several organizations and tabulated them as microcuries per milliliter at zero-time (February 14, 1976).

We review here only a few of the pertinent data. For details of the analytical methodologies and the analysts' interpretation of the results, the original reports should be consulted. The radiochemical data from U-20n PS1 DD-H (both 1983 and later) are contained in reports from LANL (Daniels 1984; Thompson 1985; Thompson 1986; Thompson 1987; Thompson 1988), LLNL (Buddemeier and Isherwood 1985; Buddemeier 1988), and REECo (Smith 1983).

Because tritium decays with a half-life of 12.3 years and because it is incorporated in the groundwater as molecular HTO (i.e., water) that does not sorb on geologic materials, tritium is considered an ideal tracer for contaminants produced underground by nuclear testing. The tritium concentration measured in 1983 was about 2.2E7 Bq/L (corrected to t_o = February 14, 1976), which is less than a third of the maximum value measured in 1976. This concentration did not change appreciably during the pumping in 1983-84. The immediate post-test concentration of tritium in the cavity water at CHESHIRE was predicted to be about 7.4E8 Bq/L. The first water samples withdrawn in 1976 were a factor of ten lower than this concentration, and the water in 1983 was a factor of thirty lower. This discrepancy is addressed in a following section as are the assumptions relative to the calculation of predicted tritium concentrations.

Both LANL and LLNL performed analyses of fission product radionuclides in water pumped from the CHESHIRE site in 1983. Table II reports some representative values from water samples analyzed with little or no filtering. While the values in Table II show close agreement between the two laboratories for some radionuclides, considerable differences exist for other radionuclides. Both laboratories subsequently extended their analytical work to include sequential filtering in an effort to identify those radionuclides that were associated with colloids and those that were in solution.

On August 1, 1984, pumping resumed at U-20n PS1 DD-H and continued intermittently until October 25; a total of 1.2E4 m^3 (3.1E6 gals) of water was produced. Analyzed radionuclide concentrations in unfiltered water collected in 1984 were similar to concentrations analyzed in samples collected in 1983. Sequential filtration of the 1984 water removed appreciable amounts of several radionuclides. Filter sizes ranged between 1000 and 6 nm. Radiochemical analysis of filtered and unfiltered waters taken from the CHESHIRE cavity indicated that most of the Mn, Co, Ce, and Eu isotopes were associated with colloidal-sized particles (Buddemeier and Isherwood, 1983). The ^{3}H, ^{22}Na, ^{99}Tc, and ^{125}Sb and substantial fractions of the ^{137}Cs generally remained in the filtrate.

As noted above, LLNL and LANL reported analytical differences in water samples collected at the same time. These differences caused the laboratories to exchange samples and conduct cross-calibrations. When residue samples were exchanged between laboratories and gamma counted, the results suggested that the agreement was within about 25% for most radionuclides (Buddemeier 1988; Thompson 1987). Larger differences, such as shown in Table II, were likely attributable to differences in sample treatment prior to the counting step. In particu-

Table II. Radionuclides in 1983 Water Samples (activities corrected to t_o = February 14, 1976)

Radionuclide	LLNL[a] (Bq/L @ t_o)	LANL[b] (Bq/L @ t_o)
^{3}H	2.27E7	2.19E7
^{22}Na	3.6E-1	3E-1
^{40}K	1.9E-1	1.9E-1
^{54}Mn	4.4E0	3E-2
^{60}Co	2.3E-1	9.6E-3
^{85}Kr	—	1.2E4
^{90}Sr	—	5.6E0
^{106}Ru	5.5E2	4E1
^{125}Sb	2.35E2	1.2E2
^{134}Cs	9.9E-1	4E-1
^{137}Cs	1.28E2	4.1E1
^{144}Ce	5.5E-1	—
^{152}Eu	4.4E-1	4E-3
^{154}Eu	7.2E-1	3E-2
^{155}Eu	2.3E0	4E-1
^{239}Pu	—	~7E-3

[a]Buddemeier 1988, p. 8
[b]Thompson 1986, p. 17

lar, the data indicated that extreme care had to be taken to prevent colloidal material from settling out or adhering to container walls.

C. 1985 Sampling and Repositioning of the Pump

Pumping continued intermittently at CHESHIRE during April and May of 1985. By May 14 about 1.3E4 m^3 (3.5E6 gals) of water had been pumped from the hole since pumping began in 1983. (After 1983 this large volume of pumped water was discharged through a pipe into an expended test site about a kilometer distant from U-20n PS1 DD-H.) The pump was withdrawn and a bridge plug set at 945 m (3100 ft) SD to isolate the lower part of the liner. The upper part of the liner was then perforated over the interval 812 to 913 m^3 (2665 to 2995 ft) SD. The pump was inserted so the intake was at 765 m (2510 ft) SD (Figures 9). Pumping resumed May 23 and continued until early November with occasional interruptions for a total yield of 3.5E4 m^3 (9.3E6 gals) of water.

The water pumped from perforations above the cavity after May 23 was compared to that pumped earlier from the lower perforations at the cavity. LANL and LLNL reported similar time-dependent trends in the data but recorded different absolute changes in the concentration of several radionuclides (Erikson 1991). The concentration of tritium was nearly the same as in 1984 (at about 1.5E7 Bq/L). Several non-sorbing radionuclides such as ^{85}Kr and ^{125}Sb showed small changes in concentration while radionuclides that sorb strongly on geologic media (e.g., ^{90}Sr and ^{137}Cs) and certain others (^{60}Co, ^{134}Cs, and the europium isotopes) showed significant decreases in concentration.

Several theories were advanced to explain the higher concentrations of radionuclides produced from the shallower interval at CHESHIRE. One held that hydrologic gradients caused water to move up the chimney to a transmissive zone in which it could then move horizontally (Buddemeier, 1988). Another held that fracture injection at the time of the nuclear test could result in radionuclide deposition outside the cavity and this could be the source of radionuclides above the cavity (Thompson, 1986). Also there was considerable uncertainty about possible movement of water up the annulus outside the liner under the impetus of pumping. If this were occurring, formation water might be contaminated with cavity water.

D. UE-20n #1

The data obtained through 1985 from the CHESHIRE site fostered differing interpretations on the evolution of the hydrologic source term and the movement of radionuclides. Participants in the CHESHIRE study hoped that additional data from a site some distance away from the post-test hole would resolve many of the ambiguities regarding radionuclide transport at this site. Therefore, a satellite hole, UE-20n #1, was drilled 300 m down gradient (southwest) from U-20n PS1 DD-H (Figure 10). Drilling of this hole was accomplished in May 1987. The total depth of this vertical hole was 1006 m (3300 ft). Most of the drilling was with air foam and three cores were collected during drilling. The hole was cased to 696 m (2282 ft) and a bridge plug and cement cap was set at 866 m (2842 ft). A Moyno pump was installed just above the bottom of the casing so that the interval (thought to be in relatively transmissive lavas identified by Blankennagel and Weir 1973) between the plug and the casing could be pumped. Details of the construction of UE-20n #1 are given in Erikson (1991).

Water samples were collected during drilling of UE-20n #1 and during periods of pumping in June, July, and October of 1987, then again in February, May, and July, 1988. Electrical conductivity and temperature logs were run between periods of pumping in June and July of 1987 (Erikson 1991; Marsh 1991). The interpretation of these logs was complicated by the presence of drilling fluids observed in the water (Thompson 1989). However, the data supported the hypothesis that warm water moved upward in the chimney at U-20n PS1 DD-H by convection and then spread laterally through the transmissive zone that was pumped at UE-20n #1.

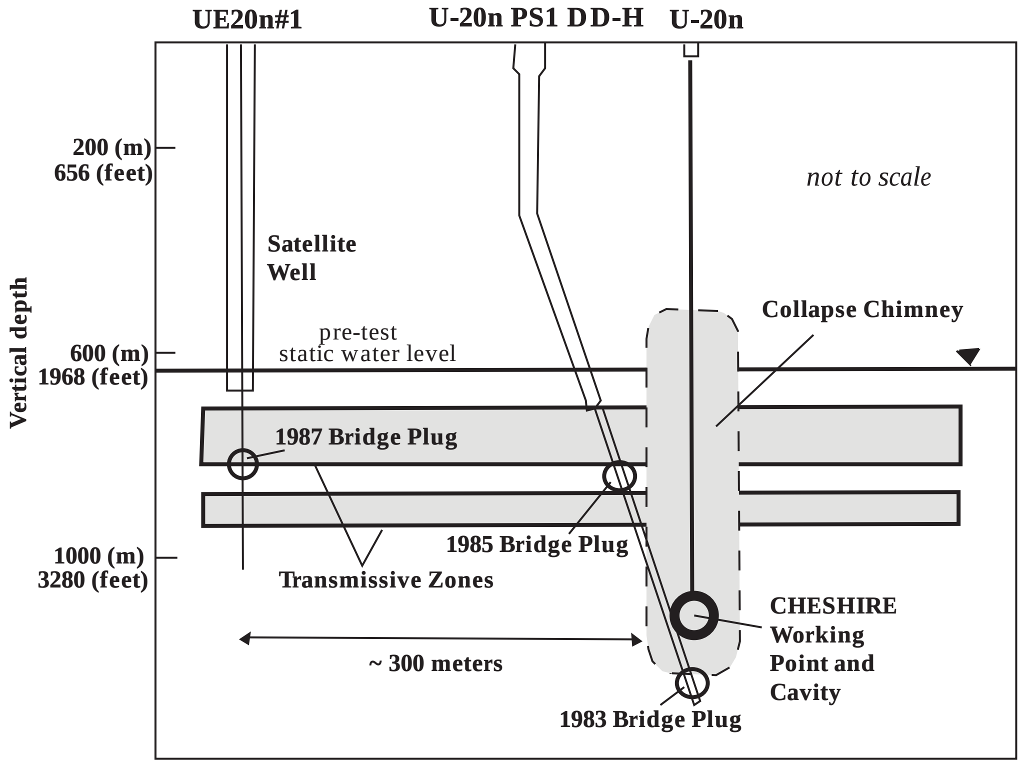

Figure 10. Vertical cross-section of the CHESHIRE study area indicating the UE20n#1 satellite well ~300 meters downgradient of the cavity and formation sampling points in U-20n PS1 DD-H. The CHESHIRE collapse chimney and transmissive aquifers above the working point are shaded.

After some 270 m^3 (7.1E4 gals) of water were pumped from UE-20n #1 the tritium concentration was 2E7 Bq/L; it rose to about 2.2E7 Bq/L with further pumping and remained at this level through the last sampling in July 1988. While not as high as tritium concentrations measured in U-20n PS1 DD-H in 1976, these values were comparable to the concentrations detected in 1983 in water drawn from the cavity region, and somewhat higher than concentrations measured from the sampling above the cavity in 1985. In order to compare concentrations of other radionuclides in the various water samples collected at the CHESHIRE site, it is useful to calculate the ratio of the radionuclide concentration to the concentration of tritium in the sample. This normalization compensates for dilution effects associated with water entering from outside the region. Table III shows these normalized changes of concentration of selected radionuclides relative to their initial concentration measured in the 1983 samples drawn from the cavity region. All values are referenced to zero-time (t_o = February 14, 1976) to emphasize changes which are not a function of the half-life of the radionuclides. Also included for comparisons are radionuclide concentrations (Bq/kg) in the melt glass.

The water sampled in 1985 above the cavity was similar to the cavity water, although the concentration of ^{90}Sr is lower. The water taken from UE-20n #1 in 1987 was depleted in mobile, conservative nuclides including ^{99}Tc and ^{125}Sb, and very depleted in strongly sorbing nuclides like ^{137}Cs (Marsh 1992a). In U-20n PS1 DD-H, the concentration of colloids in formation fluids collected from outside the cavity were approximately 50% of the concentration in the cavity and the activities of particulates were approximately 2.5% of the cavity activities (Buddemeier and Hunt 1988). These data suggest both that colloids are removed during solution transport and that colloids only incorporate a small amount of the total radionu-

Table III. Relative Concentrations of Selected Radionuclides at CHESHIRE. (All aqueous values were normalized to tritium concentrations in the same 9/83 cavity sample and decay corrected to t_o = February 14, 1976)

Radionuclide	Cavity Glass Bq/kg (06/76)	Below Cavity (09/76)	Cavity (09/08/83)	Above Cavity (06/18/85)	UE-20n#1 (10/27/87)
^{3}H	0.48	3.25	1	0.69	0.98
^{54}Mn	3E5	bdl	1	1E-2	bdl
^{60}Co	1E6	bdl	1	0.7	bdl
^{85}Kr	4E1	not measured	1	0.87	0.42
^{90}Sr	not measured	9	1	5E-2	not measured
^{99}Tc	not measured	not measured	1	1	1
^{106}Ru	4E5	5	1	1	bdl
^{125}Sb	2E4	0.5	1	0.9	0.2
^{129}I	not measured	not measured	1	1	1
^{137}Cs	4E1	bdl	1	0.4	1E-4
^{144}Ce	2E8	bdl	1	0.5	bdl
^{239}Pu?	not measured	~1?	~1?	~1?	bdl

bdl = below detection limits

clides in the cavity. However, the ability of colloids to transport radionuclides that have lower solubility (e.g., rare earth elements and actinides) is significant. Whether the colloids are generated in the cavity by hydrothermal alteration of the residual nuclear explosive melt debris or are ambient colloids that sorb radionuclides is not known, nor are potential interactions between the dissolved species, the colloids, and fracture surfaces within and adjacent to the cavity. Again, the data are consistent with a conceptual model of cavity water moving upward by convection and then outwards and down gradient from U-20n PS1 DD-H through a stratigraphically higher, transmissive aquifer. During the pumping of UE-20n #1, concentrations of iron hydroxide in the water increased. By July 1988 the water had acquired so much iron hydroxide (presumably, from iron parts rubbing within the Moyno pump) that it was of limited value for radionuclide analyses and sampling was discontinued from this hole. Despite only producing fluid for one year, valuable data on down gradient radionuclide migration was collected from the CHESHIRE satellite well (Marsh 1991; Marsh 1992a; Marsh 1992b; Thompson 1988; Thompson 1989; Erikson 1991).

We now know that the observations made at CHESHIRE are consistent with 1997 and 1998 findings at the ER-20-5 well cluster (Figure 1) where plutonium, europium, and other fission products were detected 1300 m down gradient from the BENHAM test. These radionuclides were associated with colloids and their concentrations were higher in a shallow, fractured, and transmissive welded-tuff aquifer (Kersting et al. 1998). Whether plutonium was present in U-20n PS1 DD-H waters is uncertain because all measurements for this element were at the limits of detection at that time.

V. SOURCE TERMS

A. The Radiologic Source Term

During a nuclear explosion, weapon fuels (^{235}U, ^{238}U, ^{239}Pu, ^{6}LiD) are converted to energy. The mass to energy conversion is not 100% efficient; radionuclides are both consumed and produced by the explosion.

The performance of the nuclear device determines both the amount of energy released (i.e., the radiochemical yield) and the residual radioactivity (both specific radionuclides and their abundance). Because the production of radionuclides is diagnostic of the performance of the device which is in turn derivative from the device design, the test-specific radionuclide production is always classified. Such radiochemical information is omitted from the present report; however, a test-specific radionuclide inventory will be provided in the classified CHESHIRE data report in preparation.

The ability to quantify the CHESHIRE residual radiologic source term is extremely important to an assessment of radionuclide migration. Knowledge of which radionuclides are present after the test and their individual activities allows evaluation of 1) the total inventory potentially accessible to the environment, 2) the presence of radionuclides with sufficiently long half-lives to travel to down-gradient receptors, 3) the proportion of volatile and mobile radionuclides versus their refractory and immobile counterparts, and 4) a measure of the toxicity posed by the source term. The radionuclides present underground after the nuclear test are called the radiologic source term. That fraction of the radiologic source term that can be mobilized and transported with groundwater is called the hydrologic source term. The hydrologic source term includes radioactive species which are dissolved in water or which are sorbed on particulates (e.g., colloids) that can move with groundwater. For radionuclides like ^{3}H and ^{85}Kr the hydrologic source term is identical with the radiologic source term; for refractory radionuclides such as ^{239}Pu the hydrologic source term is many orders of magnitude smaller than the radiologic source term.

The specific approach to calculating the residual radionuclide inventory for CHESHIRE is found in a classified report that provides a test-specific radionuclide inventory all underground nuclear tests fired at the Nevada Test Site (Goishi et al. 1994). An unclassified discussion of this inventory has been provided by Wild et al. (1995). In general, fission products were calculated by taking a weighted average of radionuclide yield per fast and slow fission of ^{239}Pu, ^{235}U, and ^{238}U. Activation products were estimated using computer codes and neutron transport calculations as well as nuclear cross-section data and knowledge of composition of the device, emplacement hole back-fill (stemming) and working point geology. Post-test actinide and fission fuel inventories were calculated with knowledge of the pretest actinide fuel inventory, the proportion of fast and slow neutron fission, as well as measurements of post-test actinide and fission products. The post-test tritium inventory was calculated using the pre-test tritium inventory, the fusion yield, and computer code calculations. The accuracy of the inventory for specific radionuclides follows in Table IV.

Table IV. Accuracy of Radionuclide Inventory for the CHESHIRE Test

Radionuclide by Source	Accuracy in Percent
Residual tritium	±1% to ±300%
Fission products	±10% to ±30%
Activation products	±factor of 10
Fuel activation products	±50%
Unburned actinide fuels	±20%

The radionuclide inventory calculated for the CHESHIRE test in 1994 (Goishi et al. 1994) was revised in 1995 based on results from a computer code run specifically for CHESHIRE at LLNL. The two-dimensional code revised the total device yield downward and accordingly reduced the residual tritium approximately 20% (Smith 1995b).

B. The Expected and the Observed Hydrologic Source Terms

Prior to the first sampling of U-20n PS1 DD-H in 1976, the predicted levels of radioactivity were calculated. The factors that affect these calculations are reviewed here with particular emphasis on tritium. The original expectation that the cavity water from CHESHIRE would contain tritium at a concentration of about 7E8 Bq/L was based on the calculated pretest water volume in the cavity and the amount of residual tritium estimated to be present. In fact, the highest concentration of tritium measured in 1976 was a factor of ten less than the expected amount for cavity water. Clearly, there were unanticipated factors that influenced our ability to accurately calculate the original concentration of tritium in water at CHESHIRE. The accuracy of the calculation of the concentration of tritium depended on the assumption that all of the tritium remains in the immediate vicinity of the cavity formed by the nuclear test. While experimental evidence suggests that tritium initially is dispersed in the vicinity of the cavity region, the effective volume in which the tritium is distributed may be about twice that of the cavity. Data from a number of nuclear tests show that tritium is often found outside the perimeter of the explosion cavity (the perimeter being determined principally by gamma logging during post-test drilling). Observations of tritium sited outside the measured cavity gave rise to a conceptual model for a “tritium exchange radius” where the distance of tritium deposition (from the working point) exceeds the measured cavity radius (Figure 11).

Experience at CHESHIRE corroborates radiochemical data from other test sites suggesting that volatile radionuclides other than tritium may also occupy a volume somewhat larger than the cavity. For example, ^{137}Cs and ^{90}Sr were detected outside the collapse chimney and cavity of the 1989 Ingot test in Area 2; the ratios of these radionuclides suggest that their gaseous

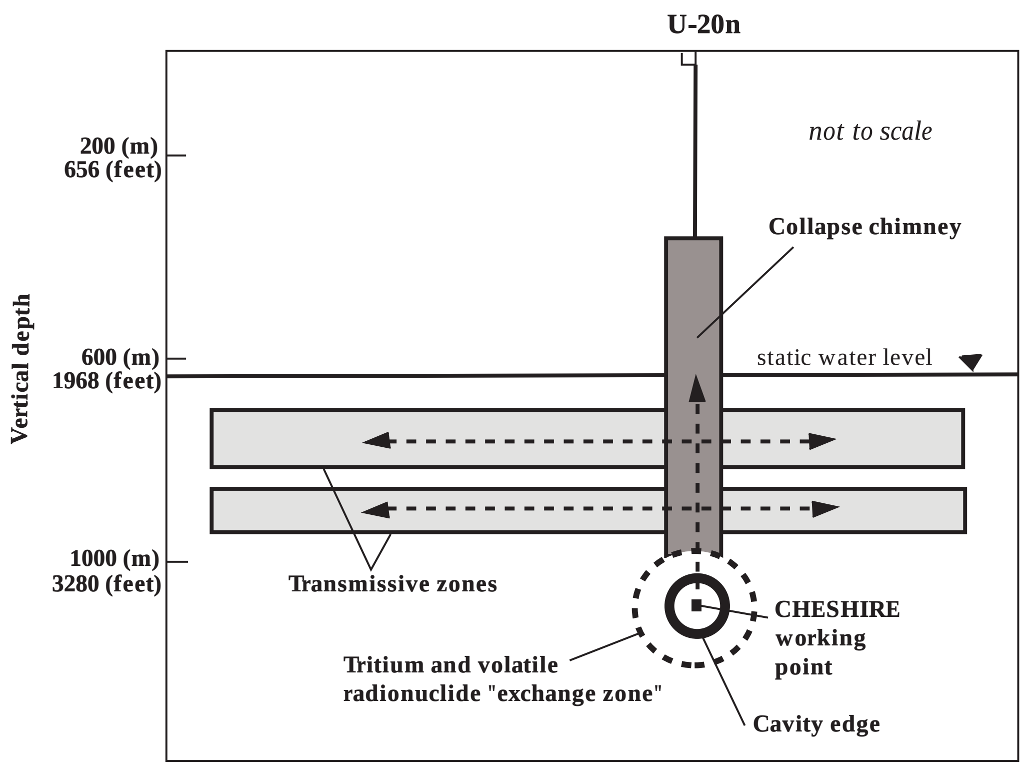

Figure 11. Conceptual model of radionuclide transport through a vertical cross-section of the CHESHIRE study area. Note tritium and volatile radionuclide exchange zone outside of the measured cavity. Heat from the explosion allows radionuclides to ascend upward through the collapse chimney to transmissive aquifers (shaded) before being transported down-gradient.

precursors (^{137}Xe and ^{90}Kr, respectively) migrated through fractures created or reactivated by the explosion for several minutes before decay to their longer-lived daughters (Smith et al.1996).

In the case of CHESHIRE, the amount of residual tritium was overestimated by approximately 20%. The volume of the cavity was calculated using measurements of the cavity radius made by gamma logging at the time of post-test drilling but was then diminished to take into account the rubble infilling following cavity collapse. We now recognize that the original volume of the CHESHIRE cavity was distributed throughout the collapse chimney which extended upward to the level of the static water table. About 98% of the tritium residual from an underground nuclear explosion condenses as molecular HTO (with 2% as HT gas) which would be well mixed with groundwater that refilled the CHESHIRE cavity and chimney after the explosion. By applying a reduction of 20% to the original estimate for the residual tritium, using a calculated cavity volume (based on a measured cavity radius), assuming complete mixing of tritium with adjacent groundwater, and employing a tritium exchange radius greater than the measured cavity radius, we now calculate an initial concentration of tritium of approximately 1E8 Bq/L. This value is in good agreement with the highest measured concentration in 1976 of 7.37E7.

^{85}Kr is a fission product with a 10.7-year half-life. Like tritium, it is a conservative tracer in groundwater. If we calculate the expected concentration of this radionuclide using the same methodology as for tritium, we get an initial concentration of 9.5E3 Bq/L. In 1976 no measurements were made of ^{85}Kr, but in 1983 the measured concentration was about 1E4 Bq/L. The good agreement between the observed and calculated values implies that the krypton produced by the nuclear explosion was also distributed in the immediate vicinity of the cavity/chimney and dissolved in the infilling water.

The CHESHIRE data contrast with those from the CAMBRIC test in Area 5 where about half of the krypton appears to have migrated upwards in the collapse chimney and escaped dissolution in the groundwater (Guell 1997).

At CAMBRIC, the chimney extends well above the water table and gases which permeated the upper part of the chimney would not have been exposed to groundwater infilling the cavity and chimney as was likely at CHESHIRE. The production of an unusually large amount of CO_2 gas may have facilitated the escape of krypton from the CAMBRIC site. Similarly, the movement of gaseous radionuclides upwards into the test chimney at the Hyrax test in Area 3 has been attributed to the fusion of large amounts of calcium carbonate ($CaCO_3$) in the alluvium which produced an abundance of CO_2 carrier gas (Thompson 1997; Smith et al. 1997). The carbonate materials required for production of CO_2 are absent at CHESHIRE. Accordingly, CHESHIRE may be a more representative model for deeply buried tests in fractured volcanic rocks with regard to retention of volatile species within the immediate vicinity of the cavity and chimney.

Calculations were done concerning the maximum concentrations of other radionuclides that might have been initially found in the cavity water at U-20n PS1 DD-H assuming a uniform distribution of the radiologic source term. These calculations yielded values of about 1E6 to 1E9 Bq/L for many radionuclides. However, as indicated in Table II above, only tritium was found with concentrations in this range. The results for other radionuclides are as expected, for a very large fraction of the radionuclides in the radiologic source term are trapped in the melt glass or sorb strongly on the surface of the rock and thus do not contribute to the hydrologic source term. The large difference between the radiologic and hydrologic source terms is verified by measurements at both the CHESHIRE and CAMBRIC sites (Kersting 1996).

VI. DISCUSSION

A. Radionuclides in the Immediate Vicinity of a Nuclear Test

In the aftermath of an underground nuclear test, tritium, fission products, neutron activation products and actinides (e.g., ^{239}Pu, ^{240}Pu, ^{235}U, and ^{238}U) are left near the test site. The spatial distribution and chemical form of these radionuclides and their relative mobility in groundwater are functions of the characteristics of each individual nuclear test (e.g., total yield, depth of burial, device design) and of the geology and hydrology of the site. As mentioned earlier, interest in the long-term effects of nuclear weapons testing on groundwater beneath the Nevada Test Site led to the initial RNM investigation of radionuclide migration away from the low yield (0.75 kt) CAMBRIC explosion which was fired in 1965 in saturated alluvium of Frenchman Flat. The CAMBRIC RNM experiment included sampling contaminated waters from both the nuclear test cavity and from a satellite well drilled 91 meters away from the working point. More than 1.7E7 m^3 (4.5E9 gals) of water was pumped from this well between 1975 and 1991. Results from this experiment indicate that the migration velocity of ^3H, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{106}Ru, and ^{129}I away from the CAMBRIC explosion cavity is nearly the same as that of the moving water. In contrast, ^{90}Sr and ^{137}Cs did not move 91 meters during the pumping period. Comprehensive reviews of the CAMBRIC experiment are provided by Hoffman and others (1977), Buddemeier and others (1991), and Bryant (1992).

The CHESHIRE test was selected as a RNM study because the test and medium characteristics differed significantly from those of the CAMBRIC site. Differences in the geologic setting of the CAMBRIC and CHESHIRE tests afforded an opportunity to compare radionuclide migration in the sand and gravel of an alluvial basin with that in fractured volcanic rocks. The yield and explosion effects of the two tests greatly differed. The yield of the CAMBRIC test was 0.75 kt; the yield of CHESHIRE was between 200 and 500 kt. At CAMBRIC, the chimney extended above the water table and volatile gases could escape from the saturated zone; at CHESHIRE, all materials appear to have been distributed below the water table. The CHESHIRE explosion generated more heat than did CAMBRIC and the resulting thermal gradients may have affected the subsequent movement of residual radionuclides in the presence of infilling groundwater. Butkovich (1974) reports on the extent of incremental heating associated with a nuclear test relative to total test yield and working point density. At a distance of ~15 m (precavity displacement) from the working point, for a rock with a density of 2.6 g/cm^3, a 1 kt explosion results in an incremental temperature increase of 10^{o}C, while for the same distance and rock density, an 100 kt explosion results in a temperature increase of 1000^{o}C.

Transport of some radionuclides was observed at CHESHIRE outside of the immediate cavity-chimney complex as groundwater moved in fractured rhyolites beneath Pahute Mesa. In contrast, at CAMBRIC there was no apparent movement of residual materials through the alluvium of Frenchman Flat prior to pumping groundwater from the adjacent satellite well. Colloid transport of radionuclides was important at CHESHIRE, but was not observed at CAMBRIC. Differences in the role of colloids as agents for radionuclide transport may be attributable to the lower natural colloid abundance in alluvium relative to fractured rhyolite or may reflect the different conditions in which refractory radionuclides were deposited in the cavity region at early times. Finally, early time radiochemical phenomenology at the two test sites differed. Radionuclides were distributed beyond the measured cavity radius at the CHESHIRE test but only below the water table. At CAMBRIC, gaseous transport allowed some radionuclides to be transported in early time through the test chimney to the vadose zone. Clearly, test yield and the site characteristics strongly affect the initial distribution of the radionuclide source term and thus the evolution of the hydrologic source term.

While the CHESHIRE and CAMBRIC tests differed in many important aspects, there were some significant similarities in post-test effects. Our field observations enable us to identify factors that control radionuclide migration away from test sites. Of particular concern are those radionuclides with half-lives in excess of ten years that are produced in abundance and could contribute to a significant radiological dose if ingested by humans. At both CHESHIRE and CAMBRIC, only a fraction of these radionuclides were available for transport by groundwater away from the cavity/chimney region. Radionuclides which were mobile in the groundwater were electrically neutral species (tritium as HTO, dissolved ^{85}Kr) or anionic species ($^{36}Cl^-$, $^{99}TcO_4^-$). Cations (e.g., $^{137}Cs^+$) were sorbed on rock surfaces and lost from solution. At both sites the movement of groundwater was the necessary agent for dispersal of radioactive materials beyond a few cavity radii. The role of hydrology must be emphasized in studies of radionuclide migration. In geologic media characterized by low permeability, such as zeolitic nonwelded tuff, the potential for radionuclide migration may be slight (Smith 1998). However, in volcanic rock aquifers with high fracture permeability, the potential to move radionuclides substantive distances down gradient is greater. Knowledge of the specific hydrologic controls on radionuclide transport at particular sites is essential for predicting radionuclide movement. Another factor that effected radionuclide migration at CHESHIRE and CAMBRIC was the vertical ascent of radionuclides through the test chimneys. At CAMBRIC the generation of CO_2 served to move gaseous radionuclides upward during and after chimney collapse. In contrast, at CHESHIRE transient temperature anomalies (the result of the heat generated by the nuclear explosion) likely caused heated water to ascend by convection as the cavity refilled with groundwater (Buddemeier 1988). In both cases, the test chimney provided a path for radionuclides to migrate upwards away from the working point. The RNM studies at CHESHIRE and CAMBRIC show how vital field observations are for understanding movement of radionuclides away from a particular test location.

B. CHESHIRE as a Model

The CHESHIRE test was chosen as a field site to study radionuclide migration because it was representative of a class of high yield underground nuclear tests detonated deep below the water table in fractured volcanic rocks. Post-test hydrologic conditions at CHESHIRE produced conditions favorable to the transport of residual radionuclides as dissolved species or as colloids. A significant number of the tests conducted on Pahute Mesa are geologically and radiochemically similar and our observations at CHESHIRE should be relevant to this larger population.

Based on our study of the CHESHIRE site, we expect volatile radionuclides to be initially (prior to cavity collapse and water infilling) distributed in a volume somewhat larger than the cavity. Most of the refractory radionuclides should be confined within the melt glass. Those radionuclides that form anions or neutral species in solution should be mobile with groundwater. Those that form cations in solution will not be as mobile unless they attach to colloids and are transported with moving groundwater. The fluid dynamics of water infilling the thermally hot cavity region may effect subsequent movement of radionuclides in the near-field. While transport of radionuclides through fractured, transmissive aquifer rocks has occurred at CHESHIRE, the role of fracture transport at other sites may differ somewhat because of variations in working point geologic media.

C. Relevance of CHESHIRE to NTS Environmental Studies

Few underground tests have been systematically investigated to identify the radiologic source term and multiyear evolution of the hydrologic source term. Synthesis of data from the CHESHIRE radionuclide migration experiment is important because no comparable set of pre- and post-test data will be obtained as long as nuclear testing is suspended. CHESHIRE provides 1) a comprehensive (and the only) measure of the radiologic and hydrologic source term at less than 1 year following a nuclear explosion within a well characterized hydrostratigraphic and fractured volcanic rock environment on Pahute Mesa, 2) valuable data on radionuclide migration from wells sampled over nearly a twenty-year interval, 3) a reference baseline where radionuclide migration has been observed and against which new samples may provide insight to the chemical pathways for radionuclides - particularly the long-lived ones – to enter into solution and be transported, and 4) initial evidence that relatively insoluble radionuclides may move conservatively by attachment to groundwater colloids. The role of colloids in transport of insoluble species is particularly significant. Analysis of water sampled from the ER-20-5 well cluster adjacent to the 1975 TYBO underground nuclear test showed that plutonium had migrated at least 1300 m down gradient from the site of the 1968 BENHAM test (Kersting et al. 1998). Plutonium, as well as fission and activation products, was retained in the residue collected on filters with pore sizes less than 1000-nm. These data may indicate that colloids could be involved in the transport of insoluble and toxic radionuclides with long half-lives (> 10 years) quickly (>40 meters/year) through fractured rock environments. The radionuclides and matrices associated with colloid transport were the same at CHESHIRE and ER-20-5.

D. Future Work at CHESHIRE

CHESHIRE provides a rare opportunity to continue studies of the transition of a radiologic source term to a hydrologic source term. Here, by sampling the cavity well at different depth intervals, we can observe the occurrence and concentration of actinides and long-lived fission products in a coupled, saturated cavity – chimney system. Also, we may observe the formation and stability of actinide-bearing colloids. Because the HRMP and ER programs already have a significant investment in the infrastructure at CHESHIRE and because we have developed an understanding of the hydrologic source term there and its dispersal away from the working point, CHESHIRE provides a logical site for continued study. Here a well-determined radiochemical model already exists for the occurrence, distribution, and concentration of significant radionuclides along a down gradient flow-path. The FY98 program at CHESHIRE, funded by DOE/NV Environmental Restoration, pumped more than 38 m^3 of water from above the bridge plug at ~ 823 m (~ 2700 ft) slant depth and more than 757 m^3 from the CHESHIRE cavity at a slant depth between 1244 m (4080 ft) and 1253 m (4110 ft). The concentration, speciation, and association with colloids of detectable radionuclides will be documented and interpreted in FY99 with reference to previous studies of this site. Continued access to CHESHIRE chimney and cavity fluids provide an unparalleled opportunity to measure the long-term evolution of the hydrologic source term more than two decades after a nuclear detonation. Investigations at the CHESHIRE site remain essential for developing a comprehensive understanding of radionuclide migration at the NTS.

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GLOSSARY

activation products	Radionuclides produced by neutron capture in elements present in materials surrounding the nuclear device (e.g., geologic media, construction materials).
bomb fraction	The part of the total radioactive material associated with a nuclear test that is contained in a particular drill back sample.
cavity	The void produced by the nuclear test. It is usually assumed to be spherical and generally is filled with rock fragments following collapse because of lithostatic pressure.
chimney	The column of broken and displaced rock that forms above the cavity as the cavity collapses. This column may extend to the surface forming a subsidence crater.
containment	The condition in which no radioactive material escapes to the atmosphere from the site of a nuclear test within 24 hours after the explosion.
device	A nuclear weapon being tested.
drill back	A drilling operation into and through the bottom of the cavity for the purpose of recovering samples of radioactive material.
ER program	The environmental restoration program at the Nevada Test Site sponsored by the Department of Energy, Nevada Operations Office.
gaseous precursors	Radioactive gaseous elements that decay to daughter elements that are not themselves gases.
ground zero	A point on the surface of the ground vertically above the location of the nuclear test.
HRMP	The hydrologic resources management program sponsored by DOE/NV. Participant organizations include Los Alamos National Laboratory, Lawrence Livermore National Laboratory, the Desert Research Institute, the U.S. Geological Survey, and several contractors at the NTS.
half-life	The time required for half of a population of radioactive atoms to decay to daughter atoms.
hydrologic source term	Radionuclides associated with a nuclear test that may be transported by groundwater either in solution or as colloids.
HTO	A water molecule in which one of the hydrogen atoms is replaced with a tritium atom.
RNM	The radionuclide migration program; the predecessor to the HRMP.
radiologic source term	Radionuclides associated with a nuclear test.
radionuclide	A radioactive atom.
stemming	The process of filling a drill hole to prevent radioactive material associated with a nuclear test from escaping to the accessible environment.
working point	The location underground at which a nuclear test is conducted.
zero time	The time at which a nuclear test occurred.